Ultracold molecules

Dr. Alessandro Zenesini
CNR-INO
Pitaevskii BEC Center, University of Trento

Introductory Course on Ultracold Quantum Gases 2023, Innsbruck

Life is a matter of interactions

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- 2: Basic concepts on two-body interactions
    - Scattering length
    - Feshbach resonance
- 1+1: Let’s stay together
    - How to cool them
    - Basic experiment
- 3: Good/Bad things come in threes
- 4 and more: It’s time to party

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Two-body interactions

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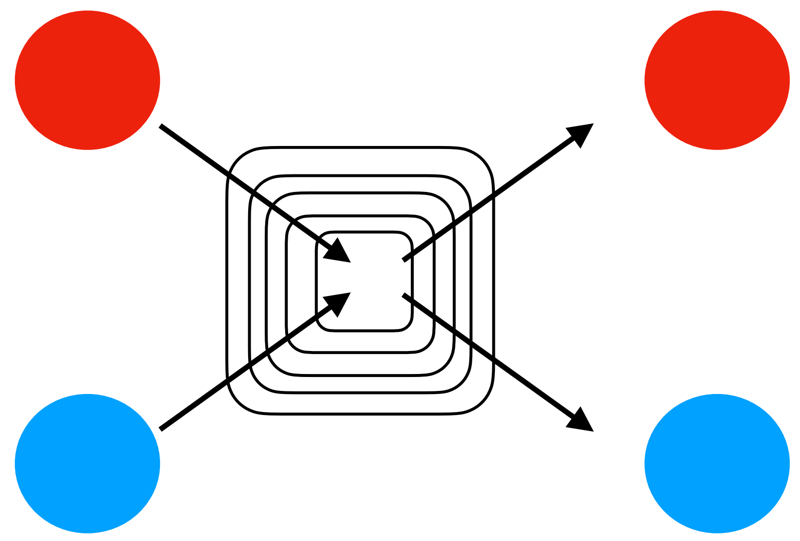
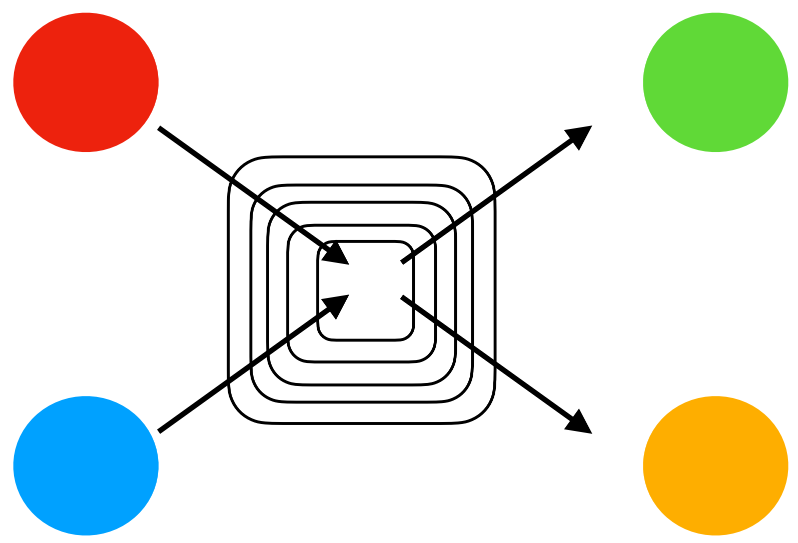


Elastic collision
Energy conserved
Total angular momentum conserved



Inelastic collision
Internal energy converted to kinetic energy (or viceversa)
Total angular momentum (internal + collisional) conserved

Two-body interactions

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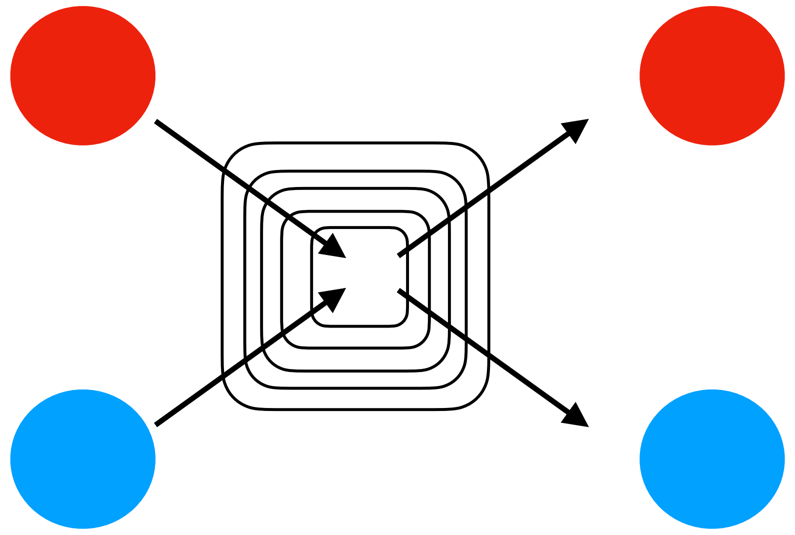

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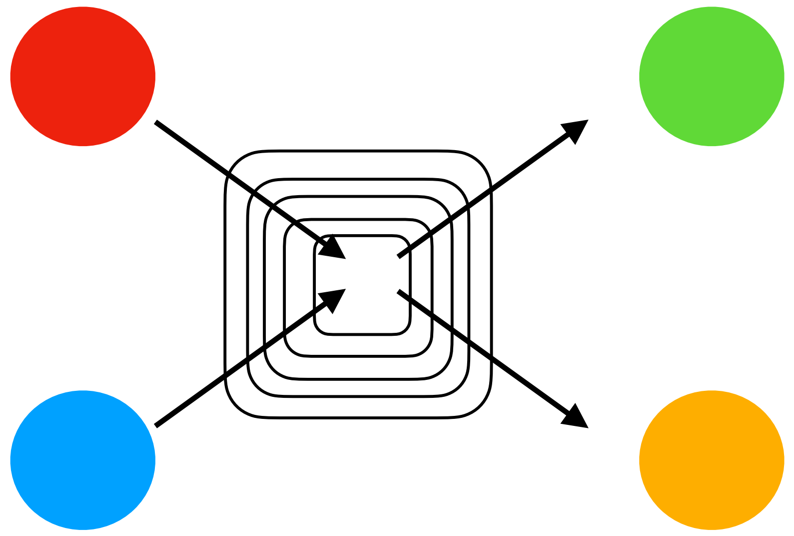

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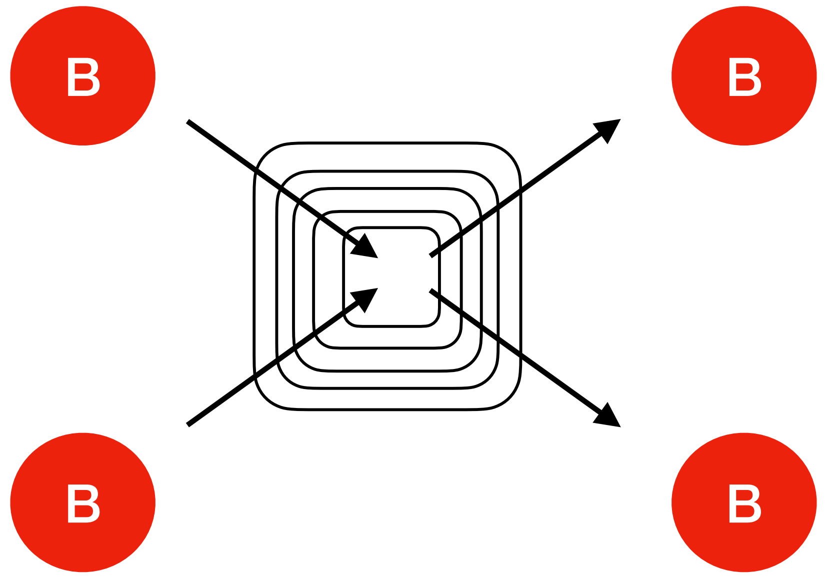

Symmetric wave-function

Two-body interactions

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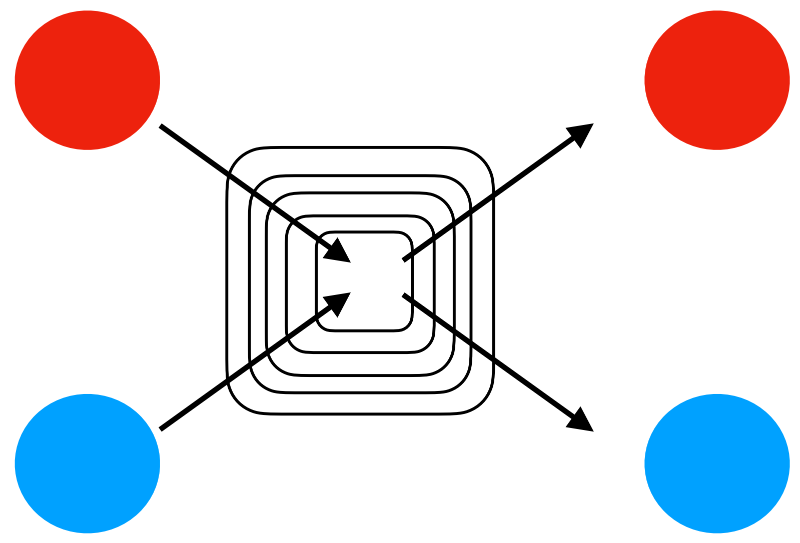

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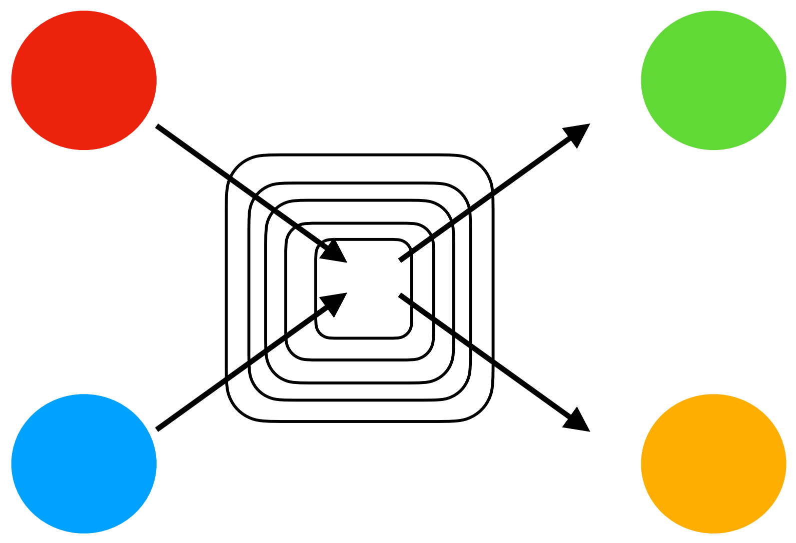

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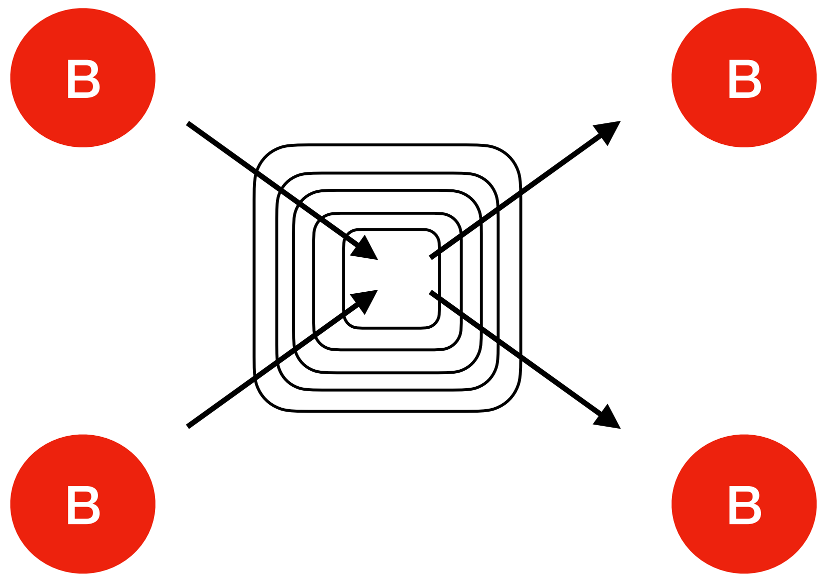

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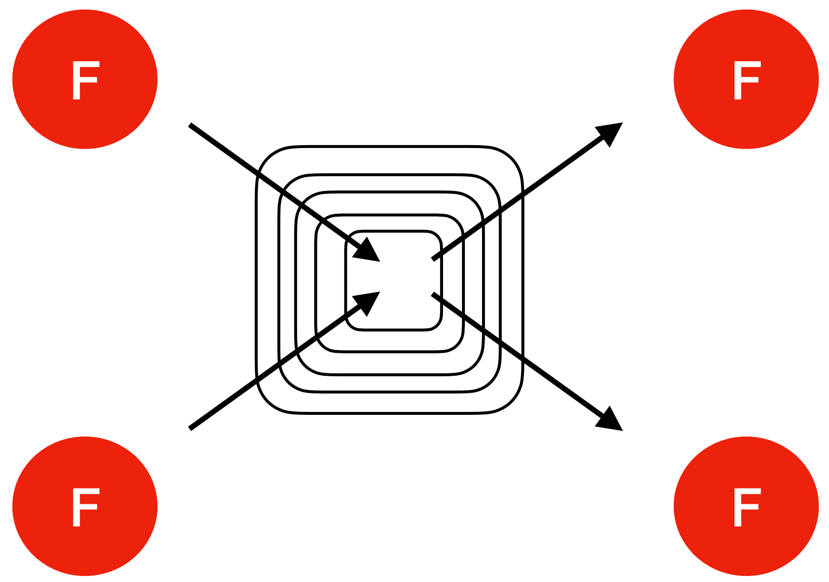
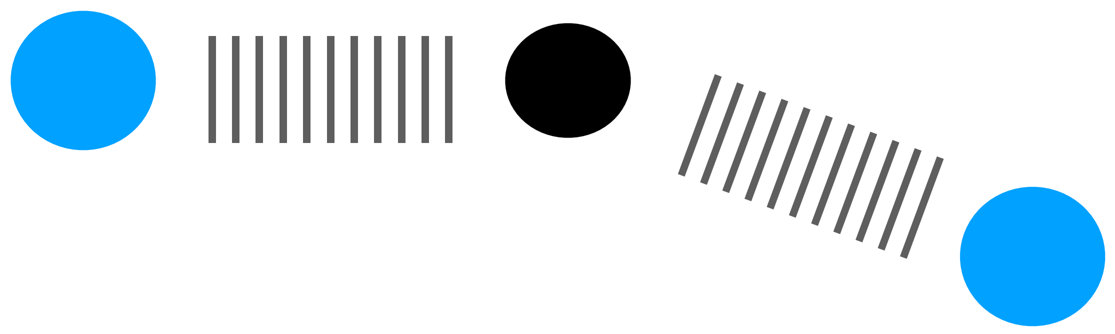


Anti-symmetric wave-function

Scattering length



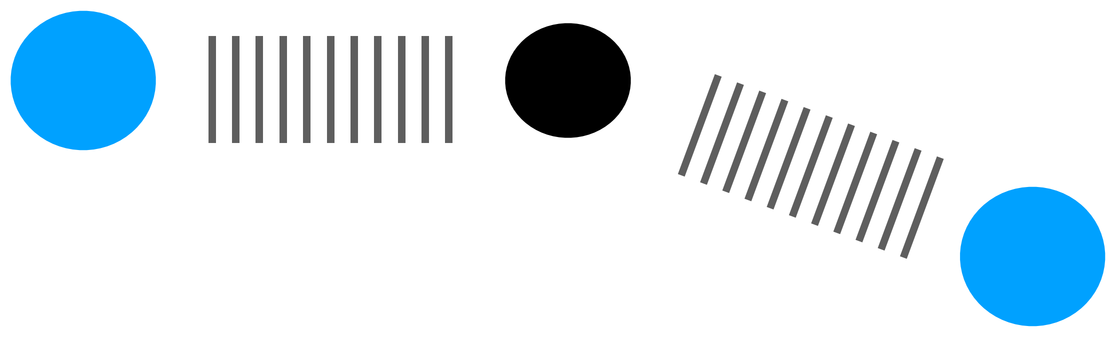
The scattering length is classically the size of the target

Quantum: Scattering between waves
Outgoing scattered wave decomposed in spherical harmonics

For example:

symmetric target -> symmetric output

Scattering length



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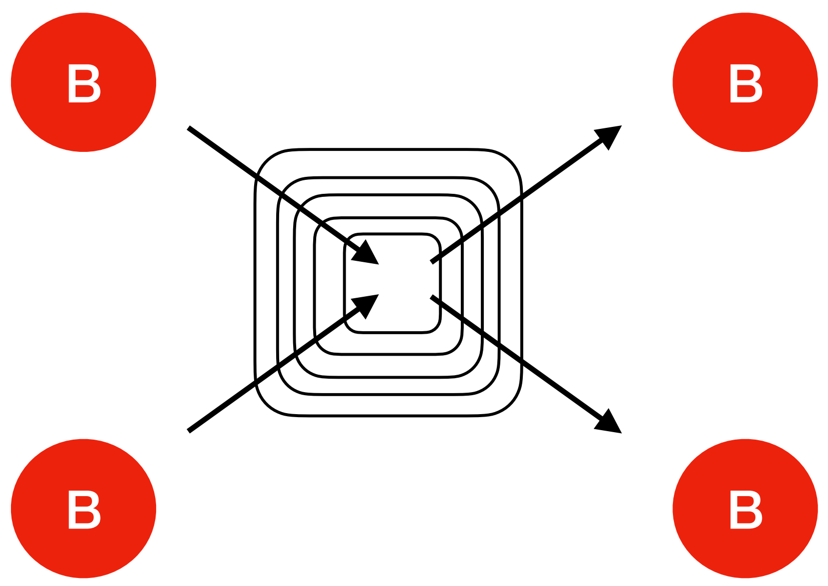

Identical particle
Symmetric wave-function

Only s-wave and even

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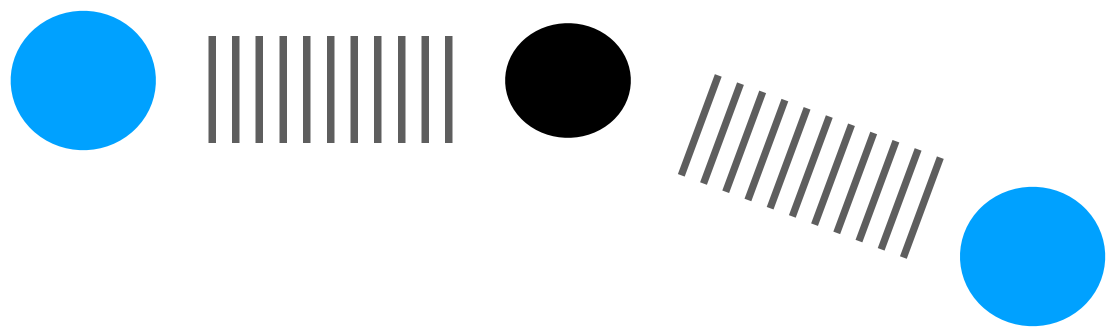
Scattering length



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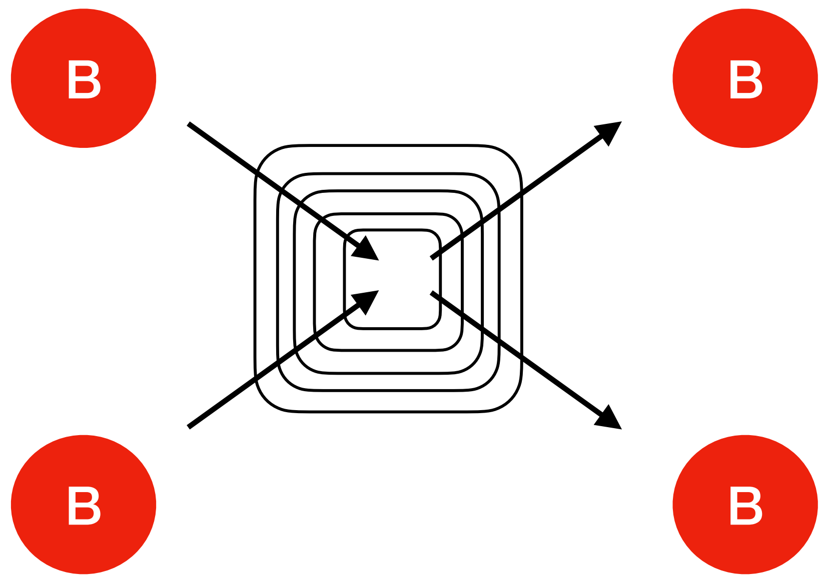

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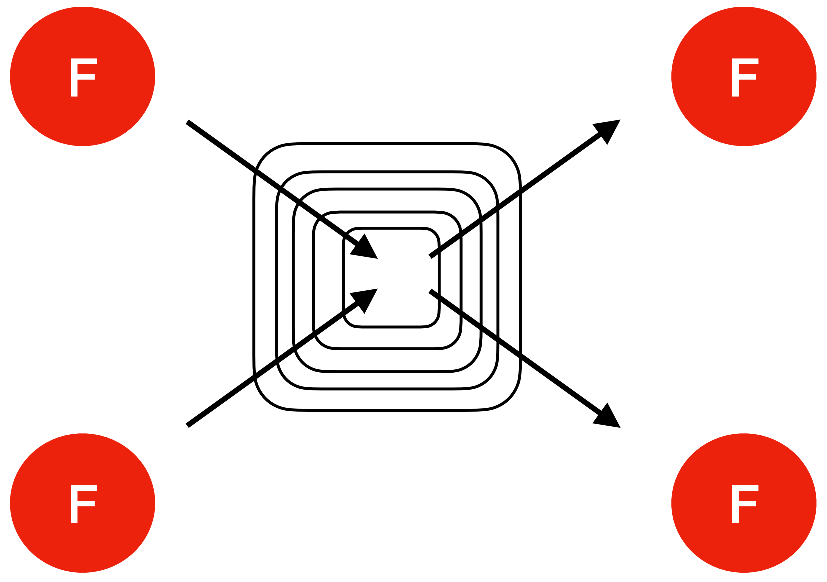

Identical particle
Anti-symmetric wave-function

Only p-wave and odd

Scattering length

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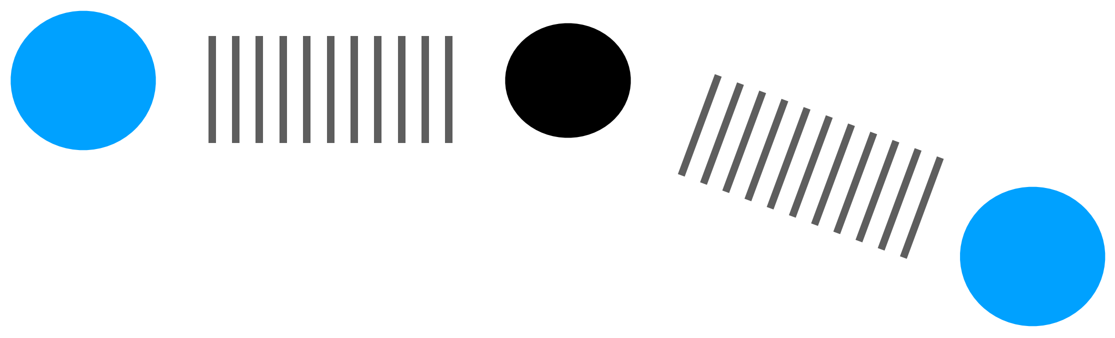

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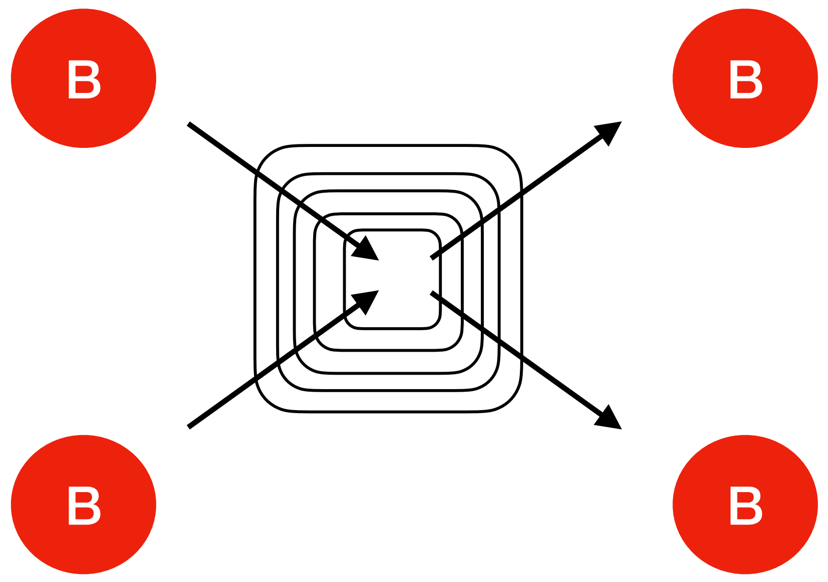

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Symmetric wave-function

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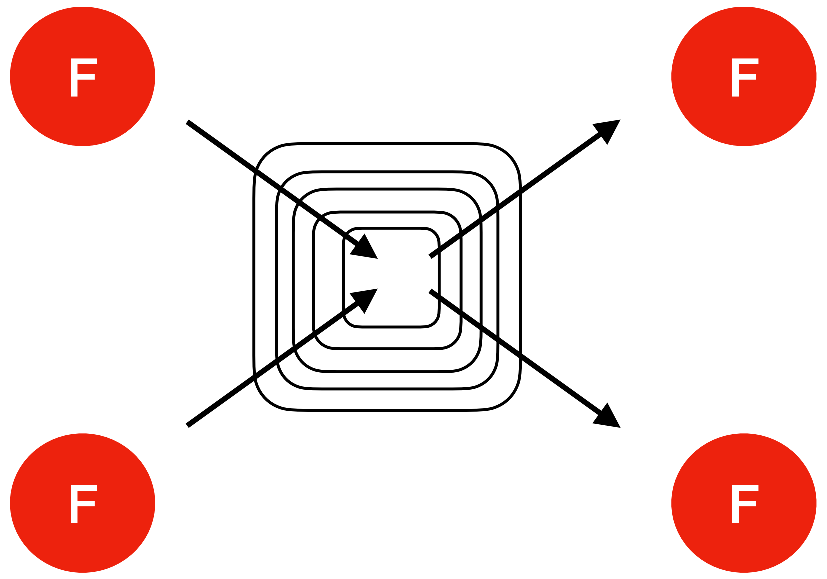

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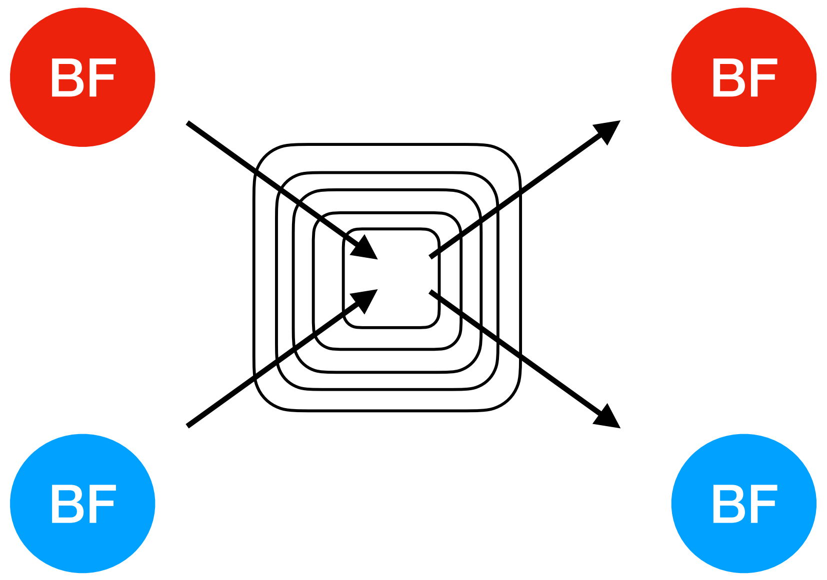

Distinct particle
Whatever wave-function

s-wave and all

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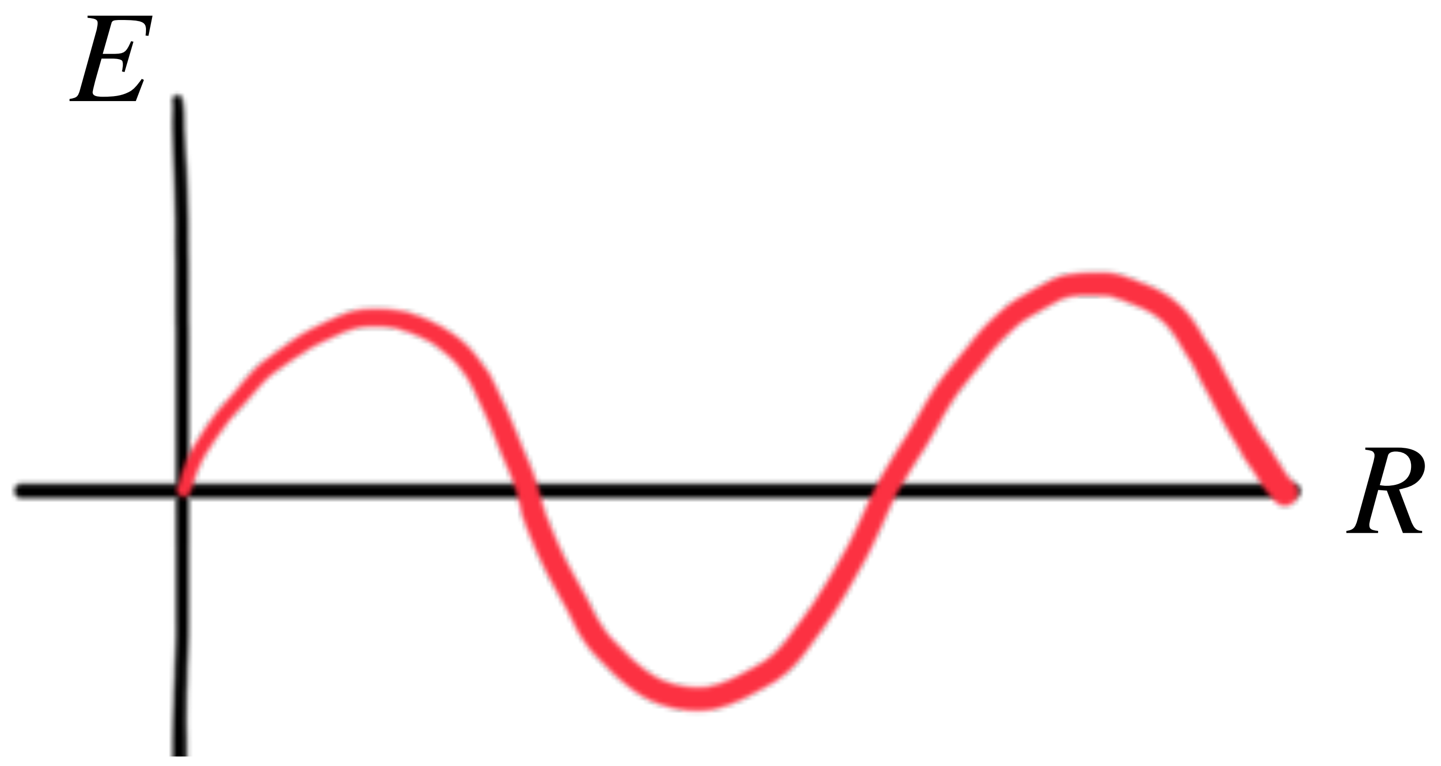
Interaction potential, the phase shift and the scattering length



Interaction potential, the phase shift and the scattering length

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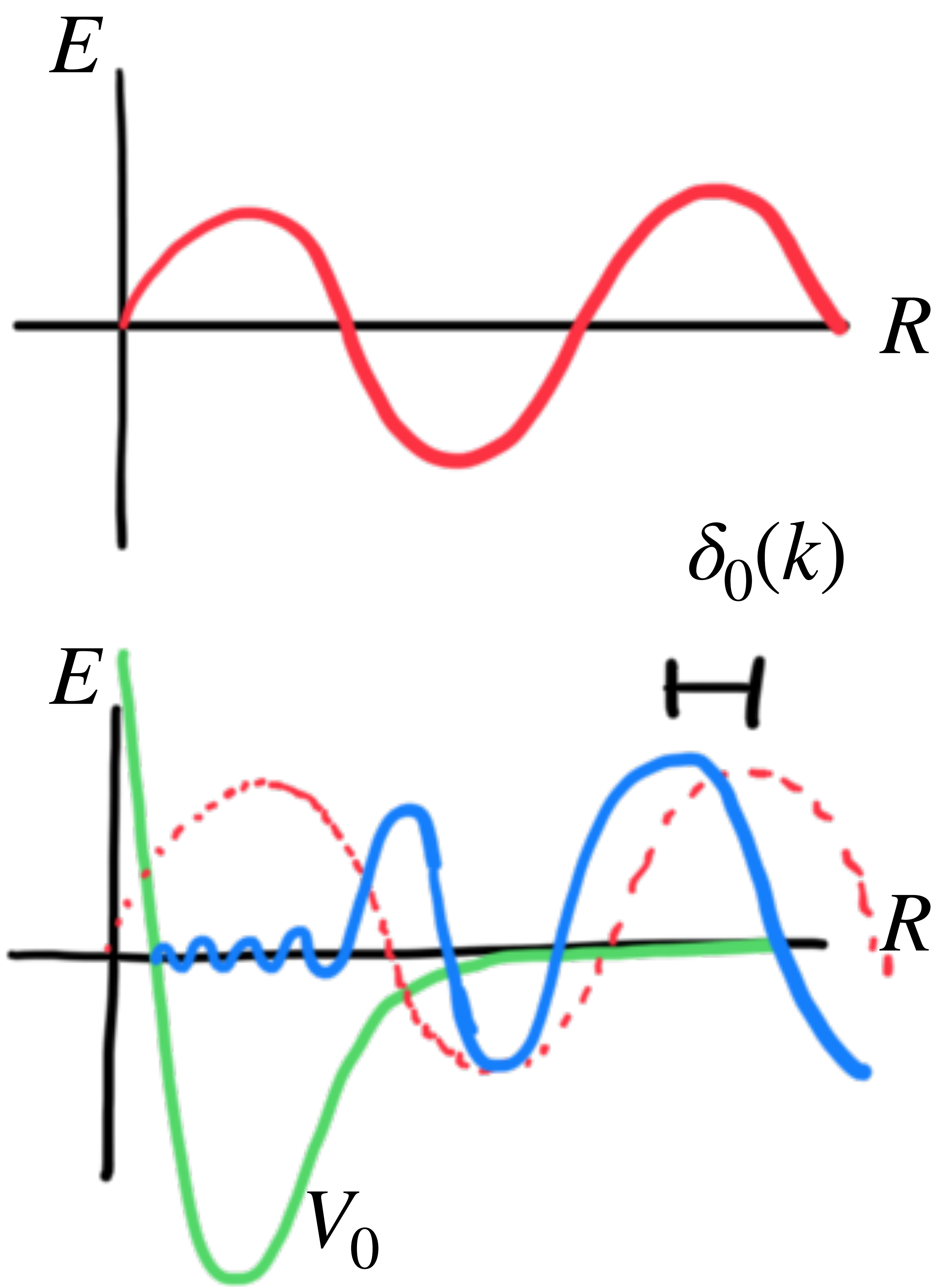
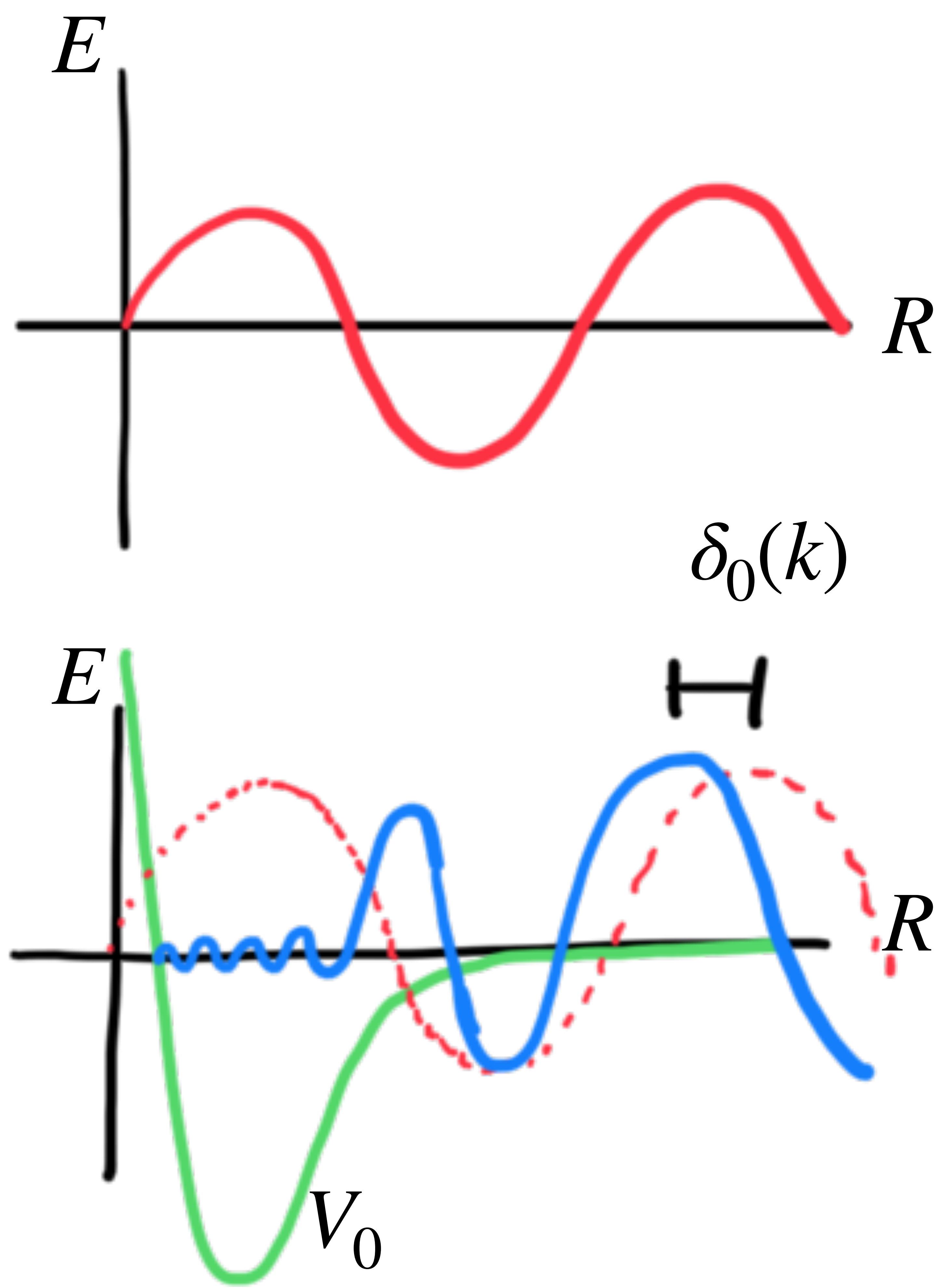


Interaction potential, the phase shift and the scattering length



$$a = -\lim_{k \to 0} \frac{\delta_0(k)}{k}$$

The role of the molecular potential

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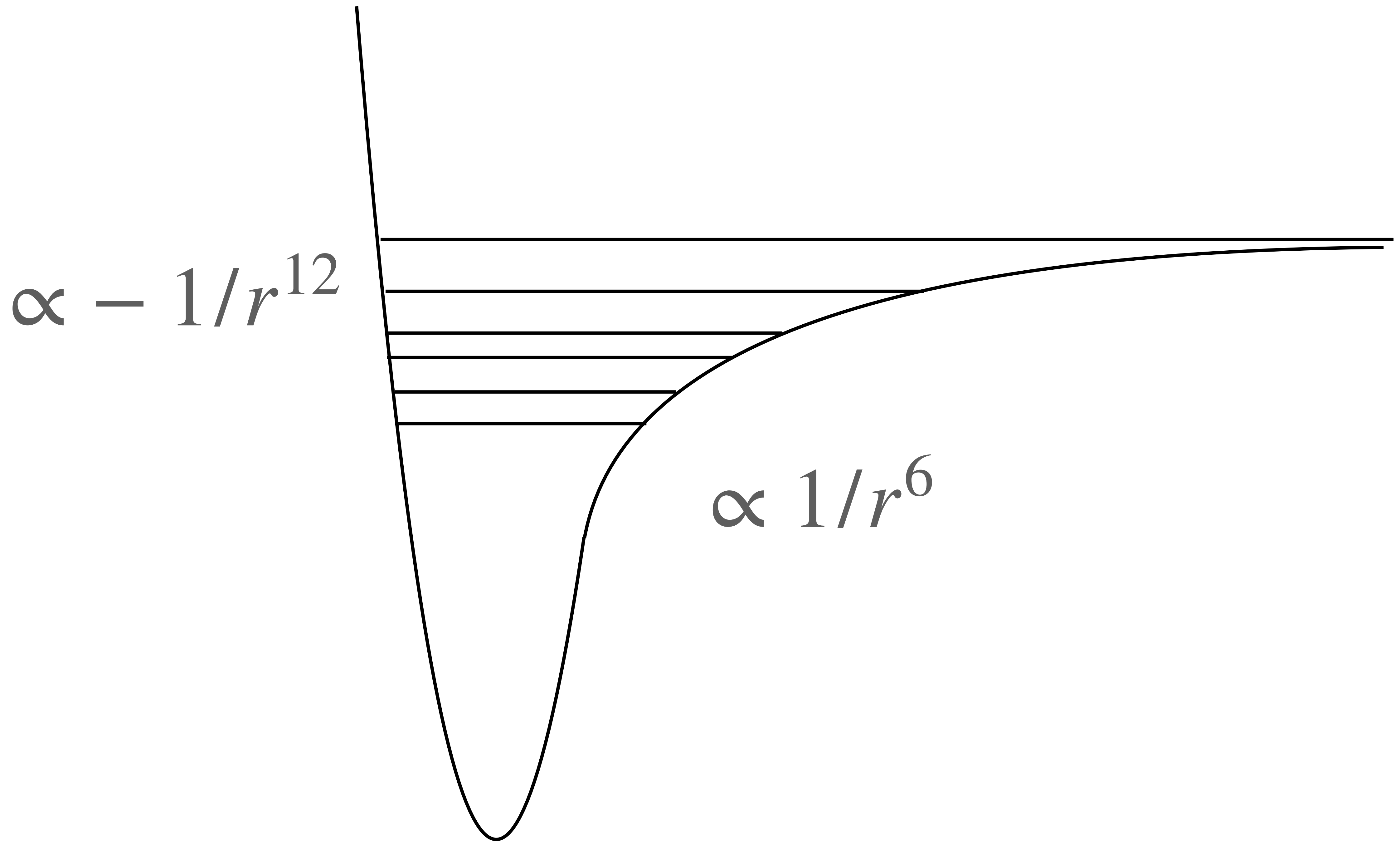

Interaction potential
=
Molecular potential

Which is the connection between bound states and scattering length?

The role of the molecular potential

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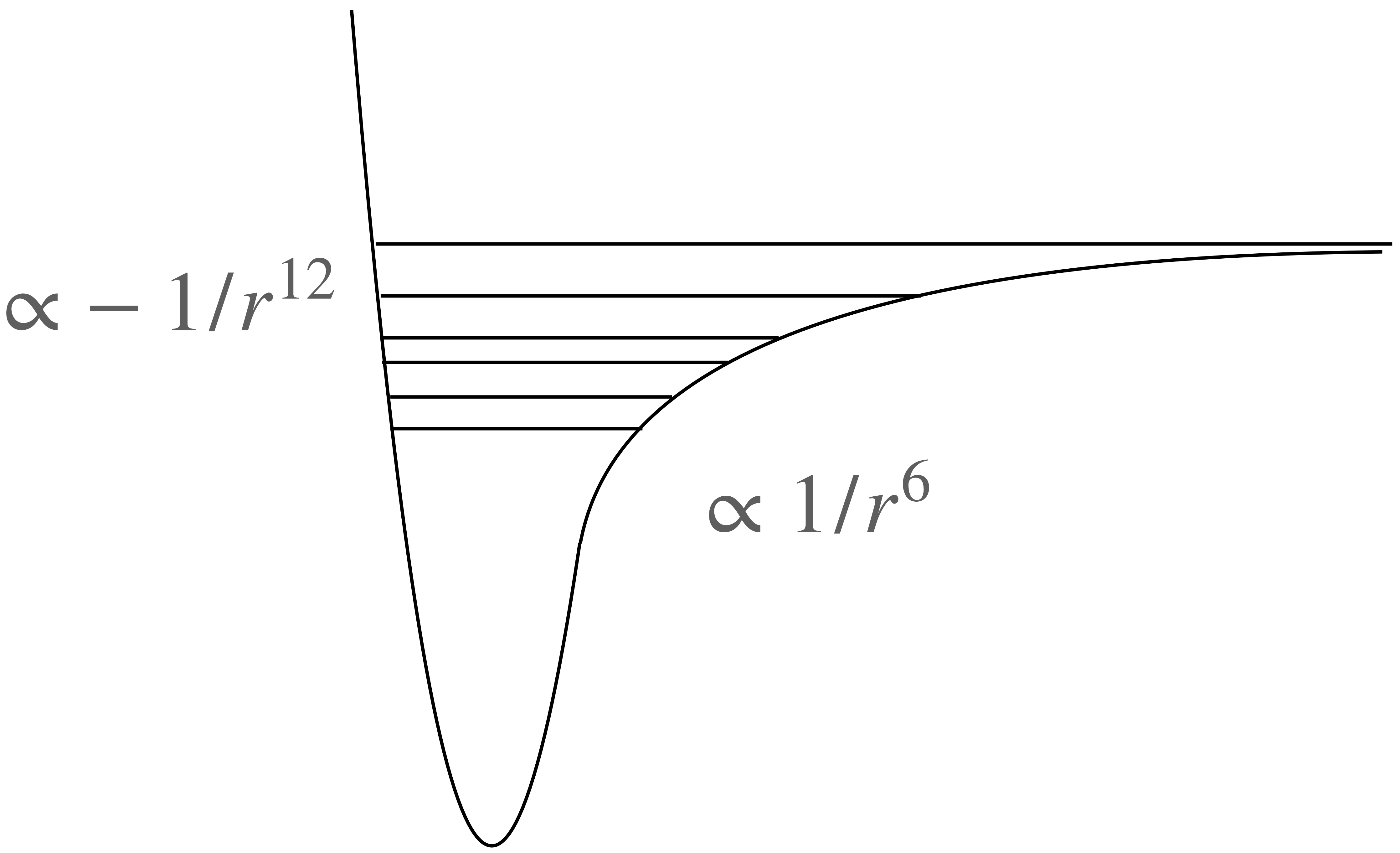

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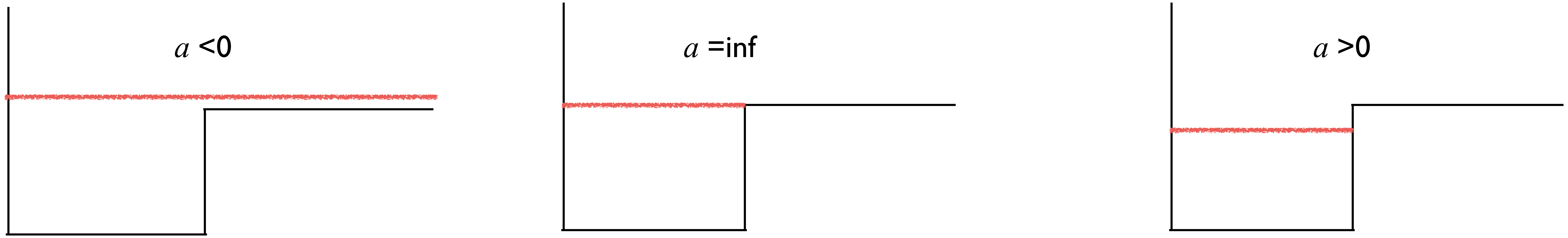

The role of the molecular potential

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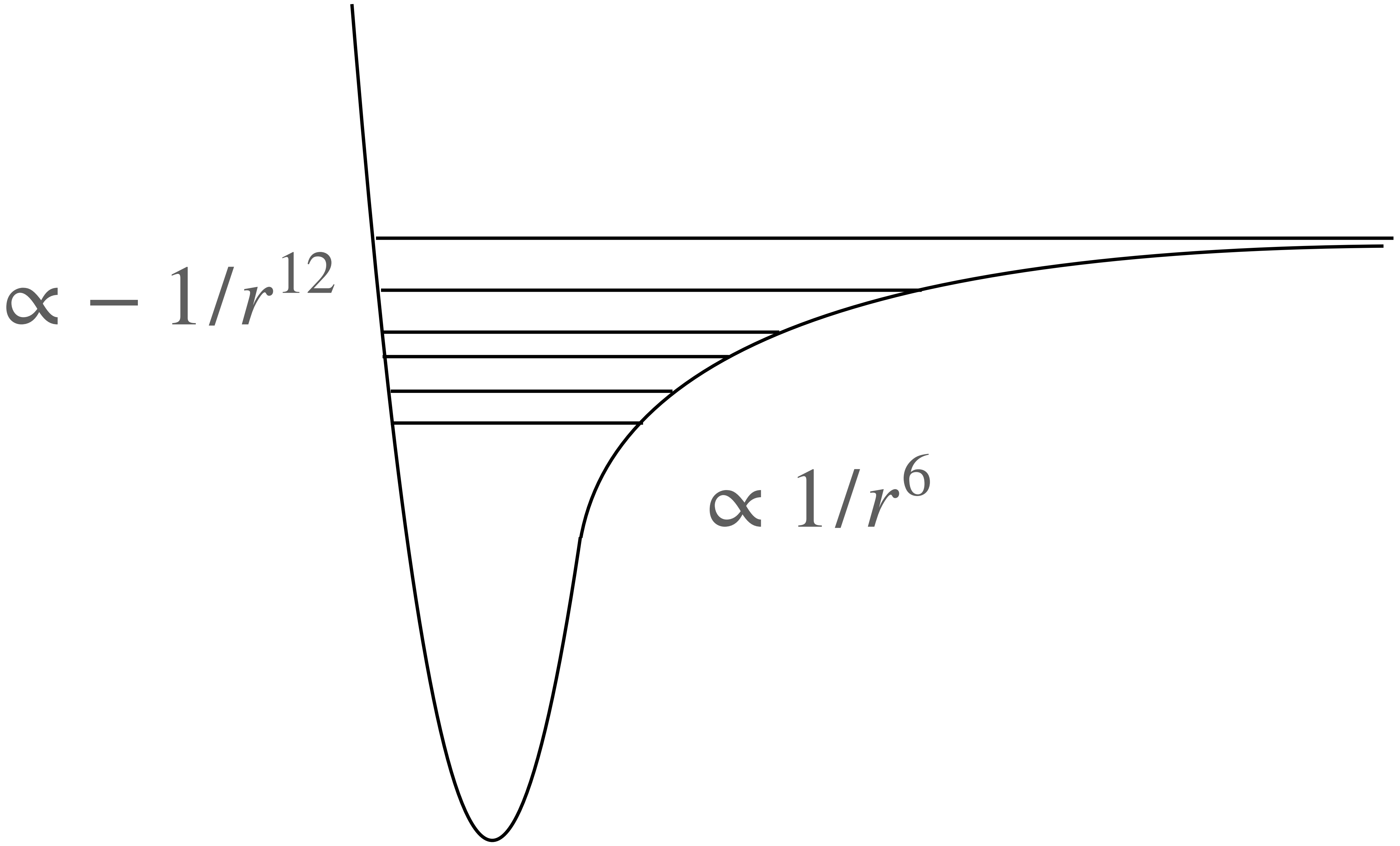

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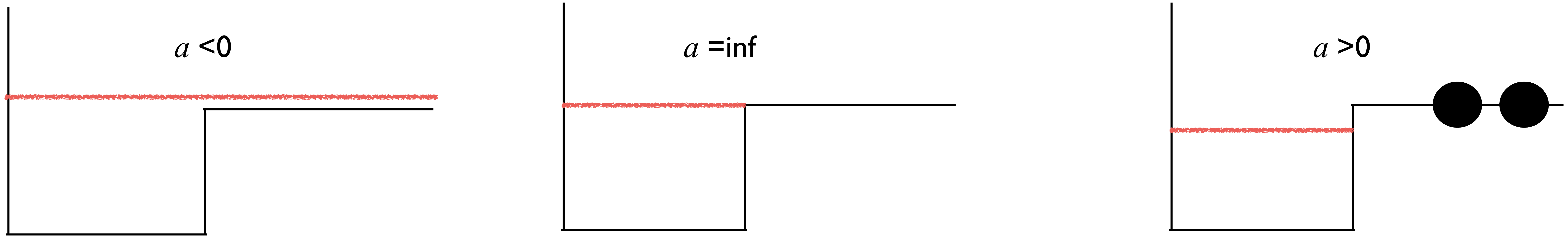

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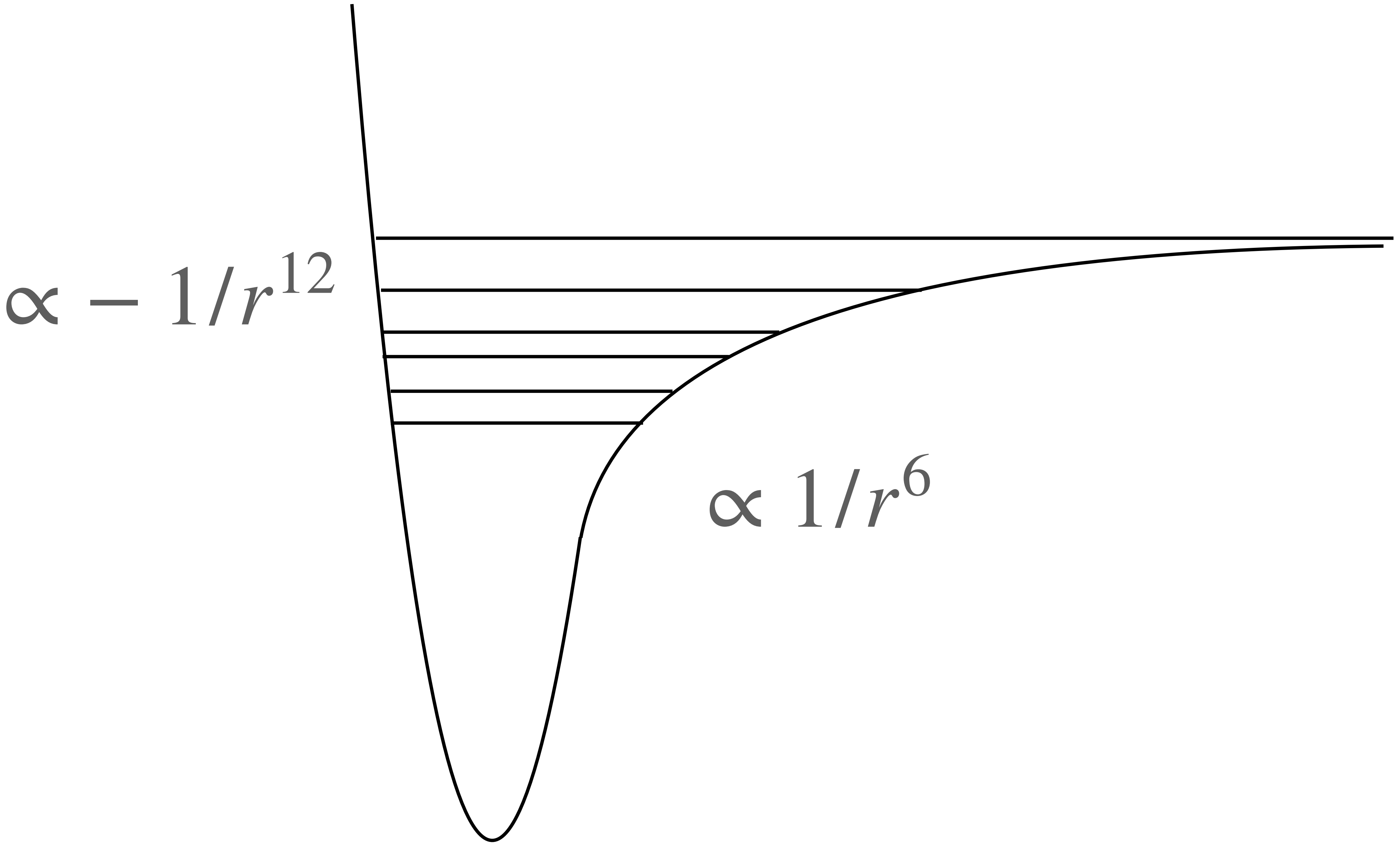

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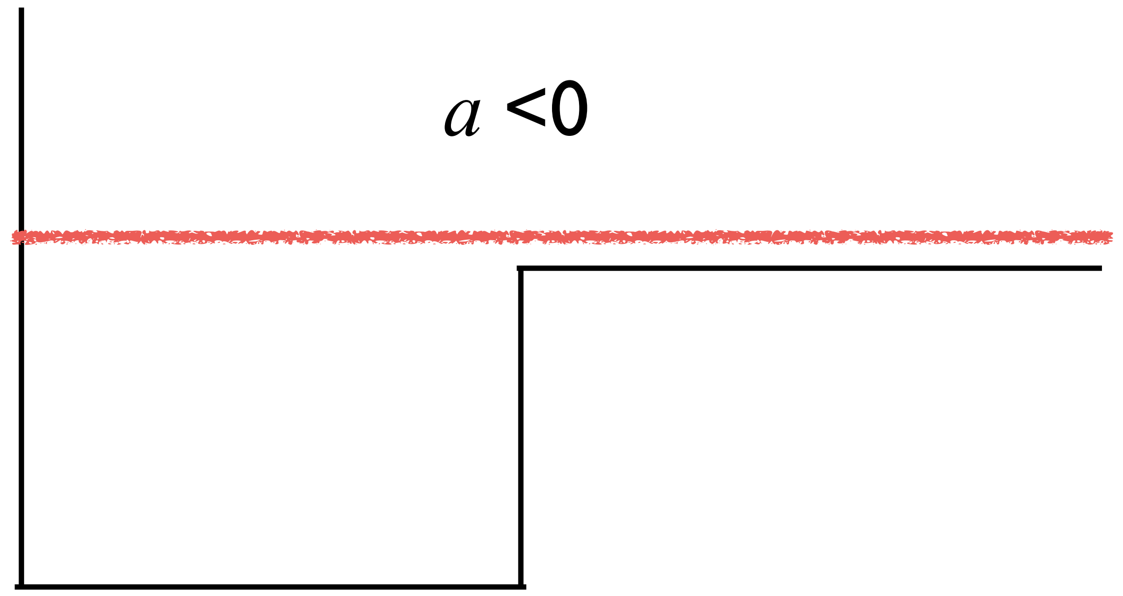

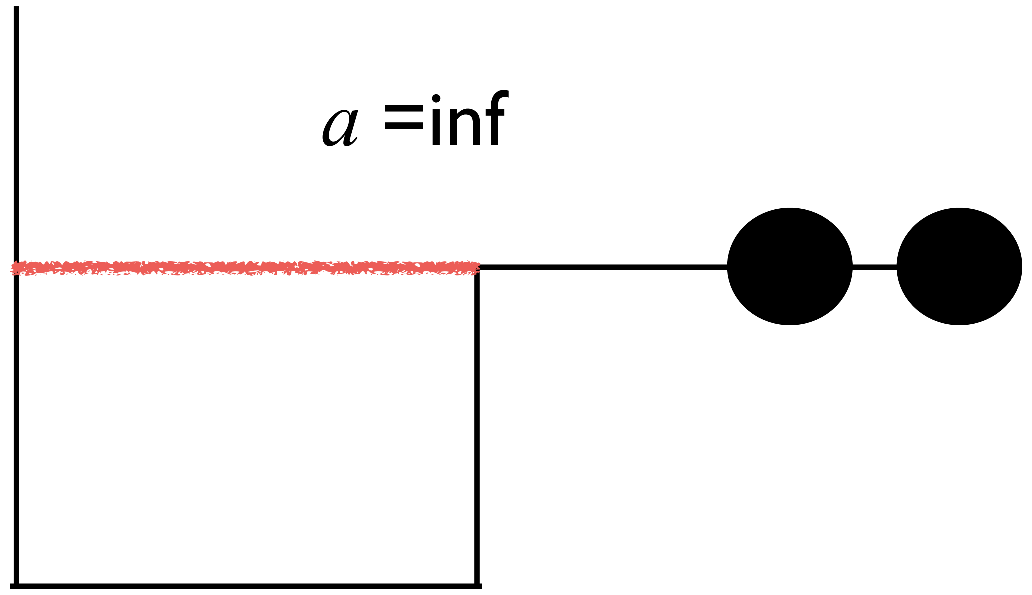

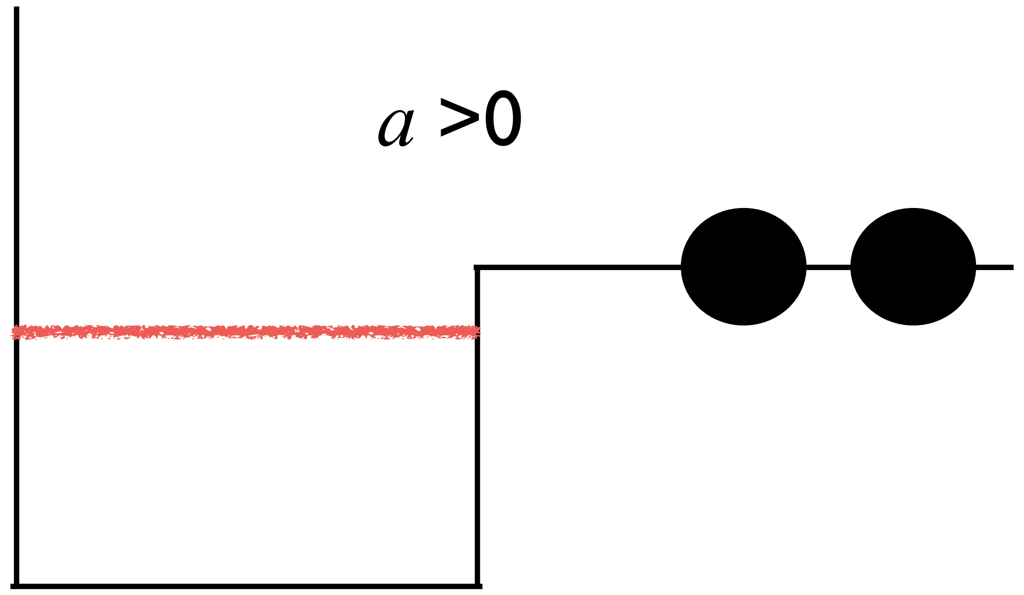

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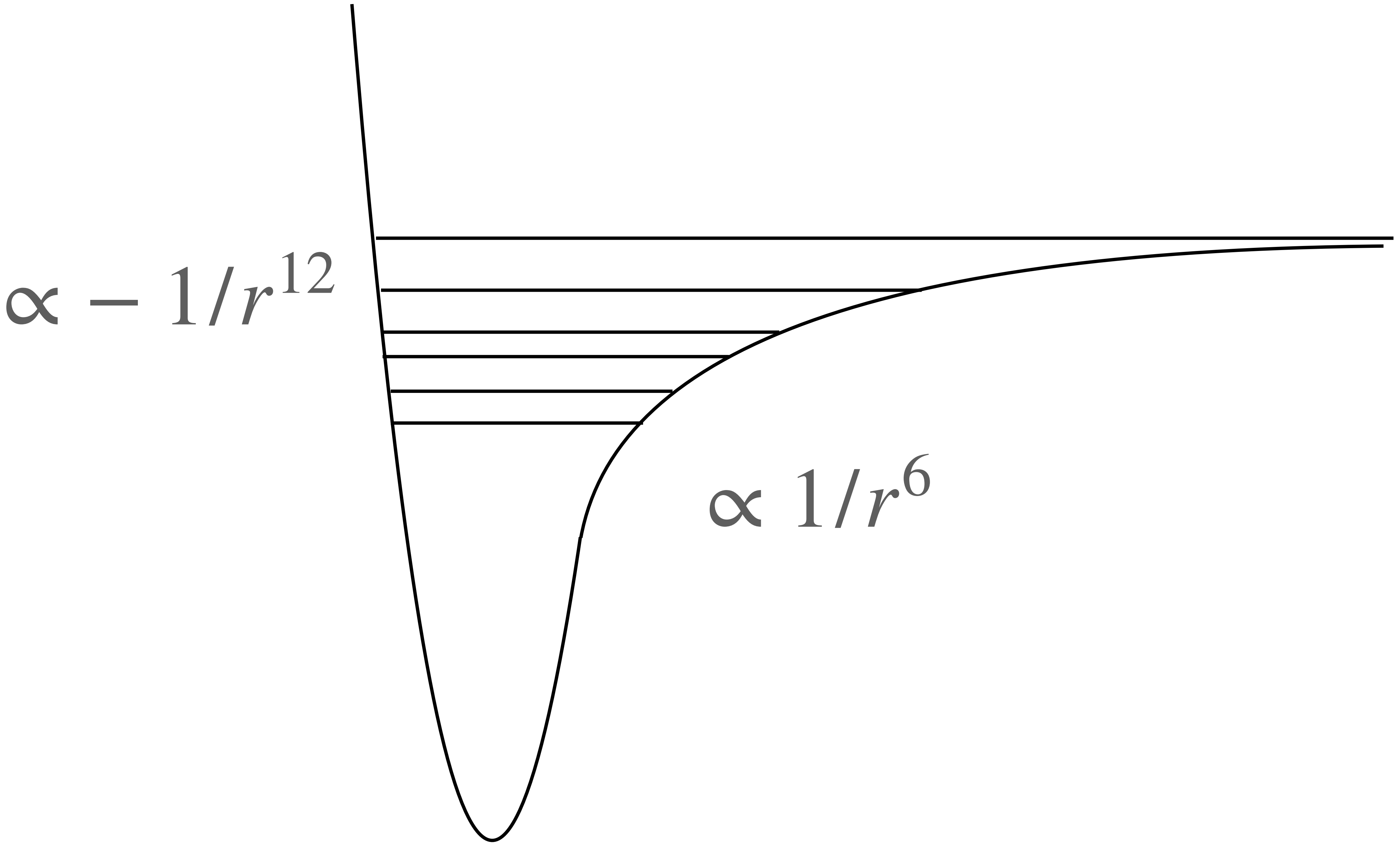

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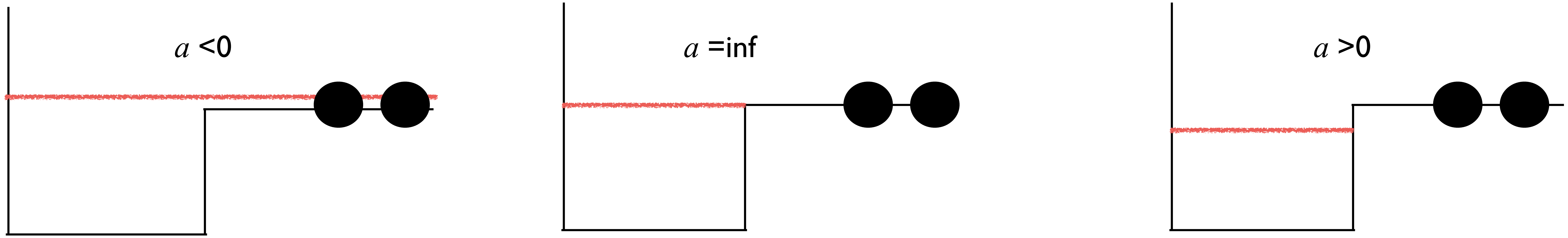

Scattering length tuning: Feshbach resonance

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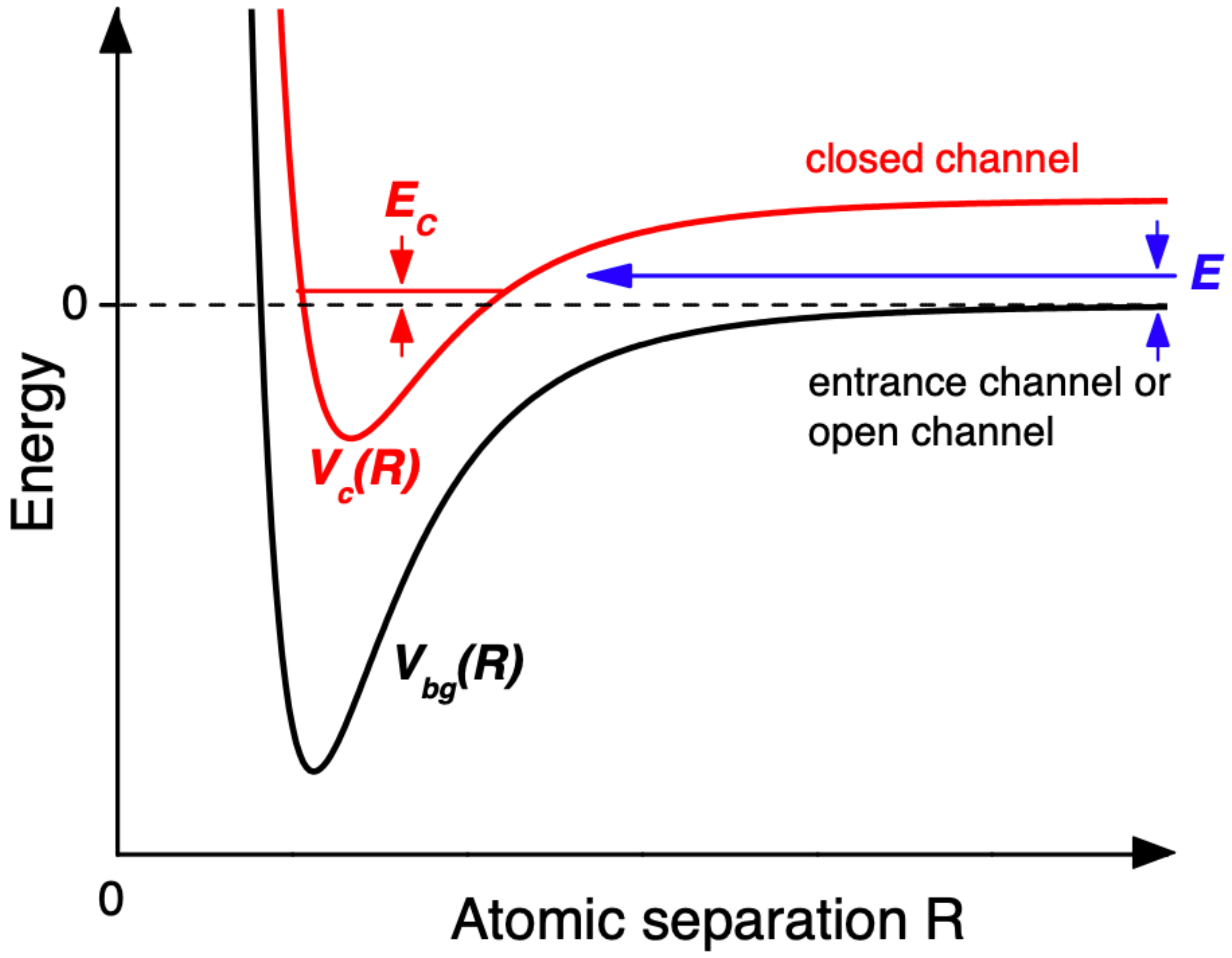
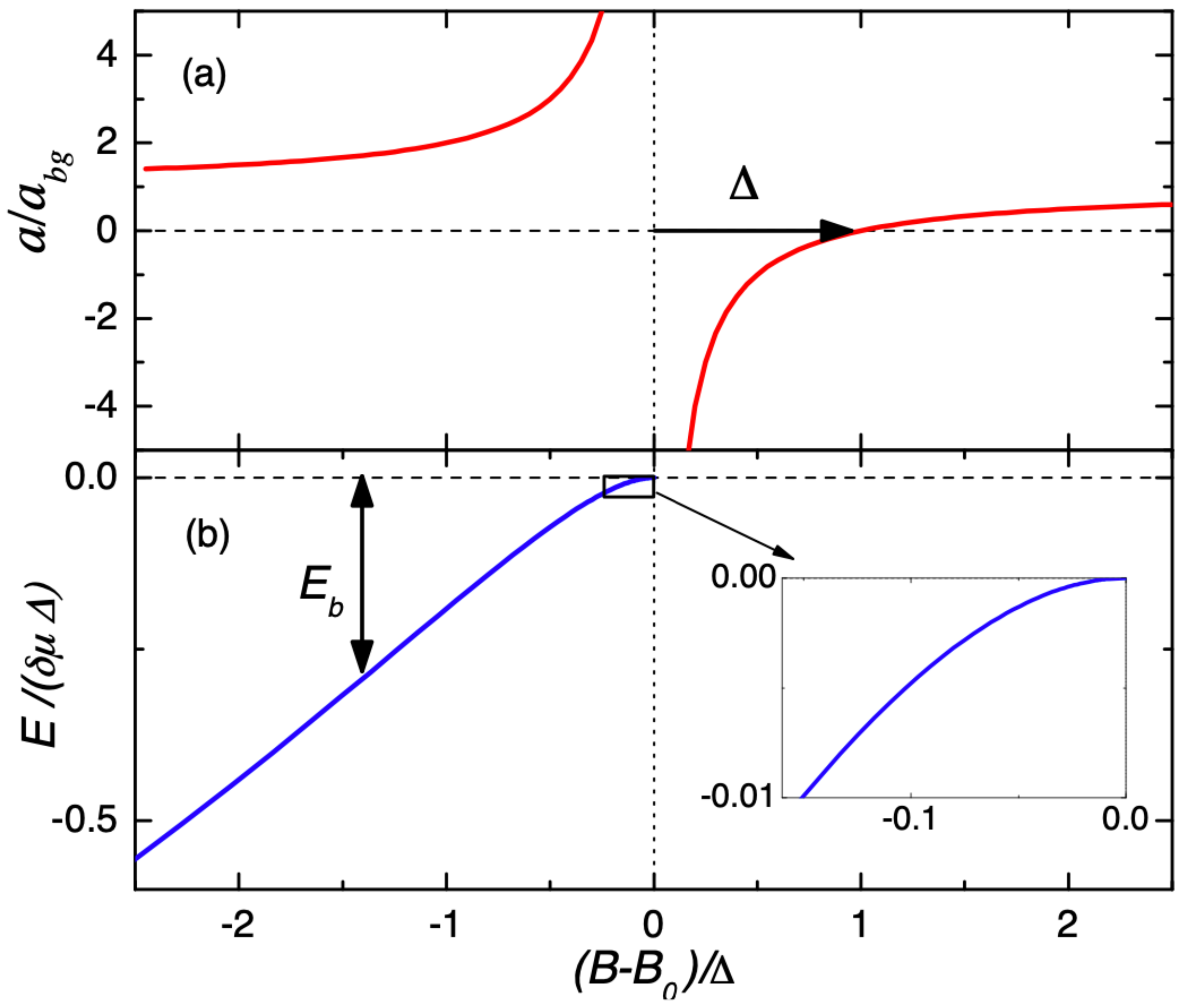


$$a(B) = a_{\rm bg}\left(1 - \frac{\Delta}{B - B_0}\right)\,.$$



Feshbach resonances in ultracold gases

Cheng Chin, Rudolf Grimm, Paul Julienne, and Eite Tiesinga
Rev. Mod. Phys. **82**, 1225 – Published 29 April 2010

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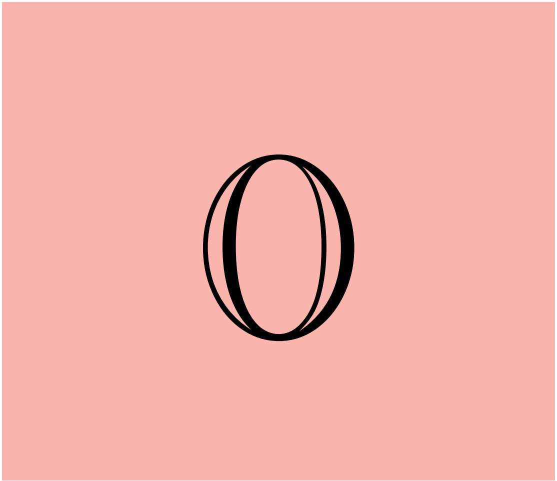

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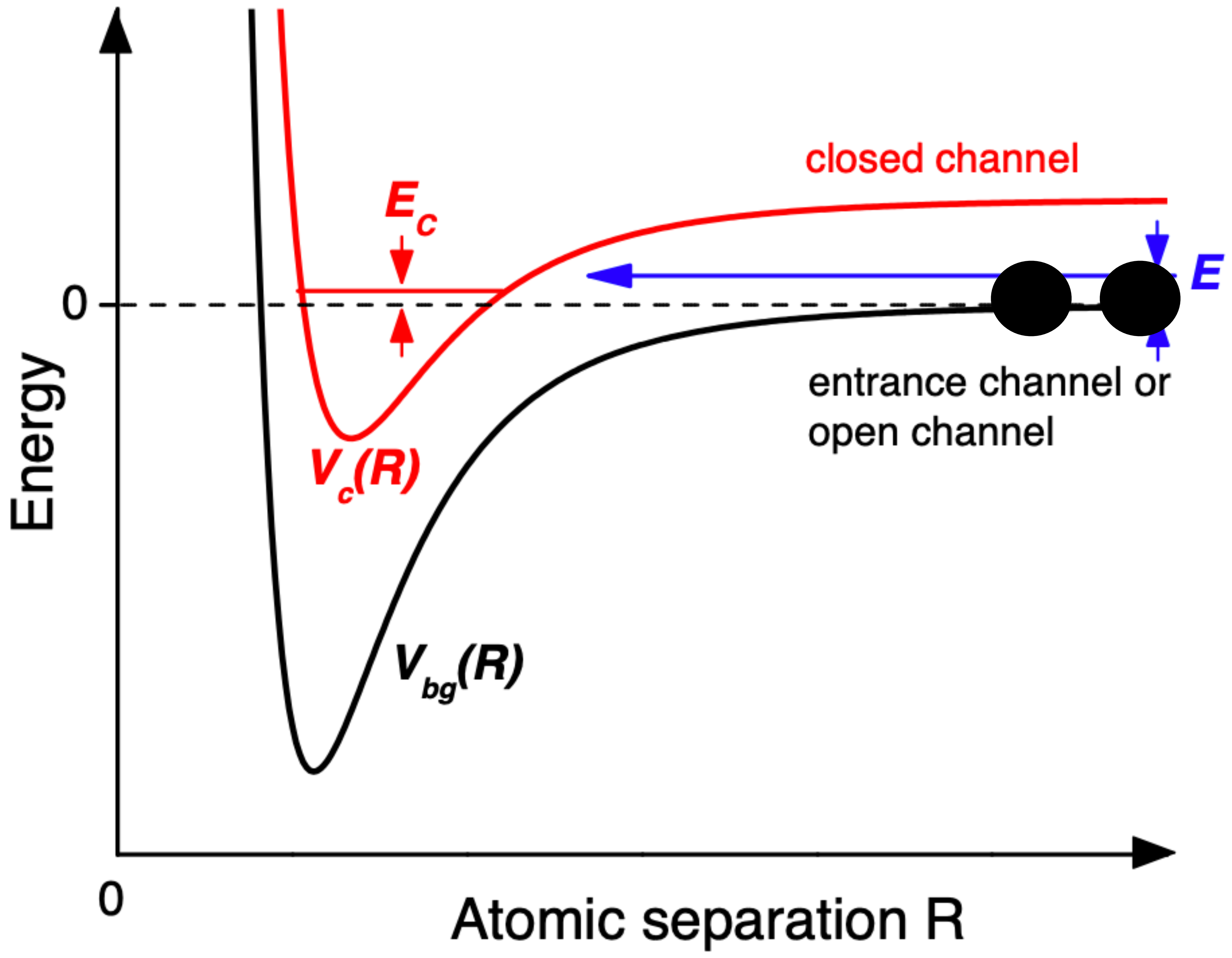

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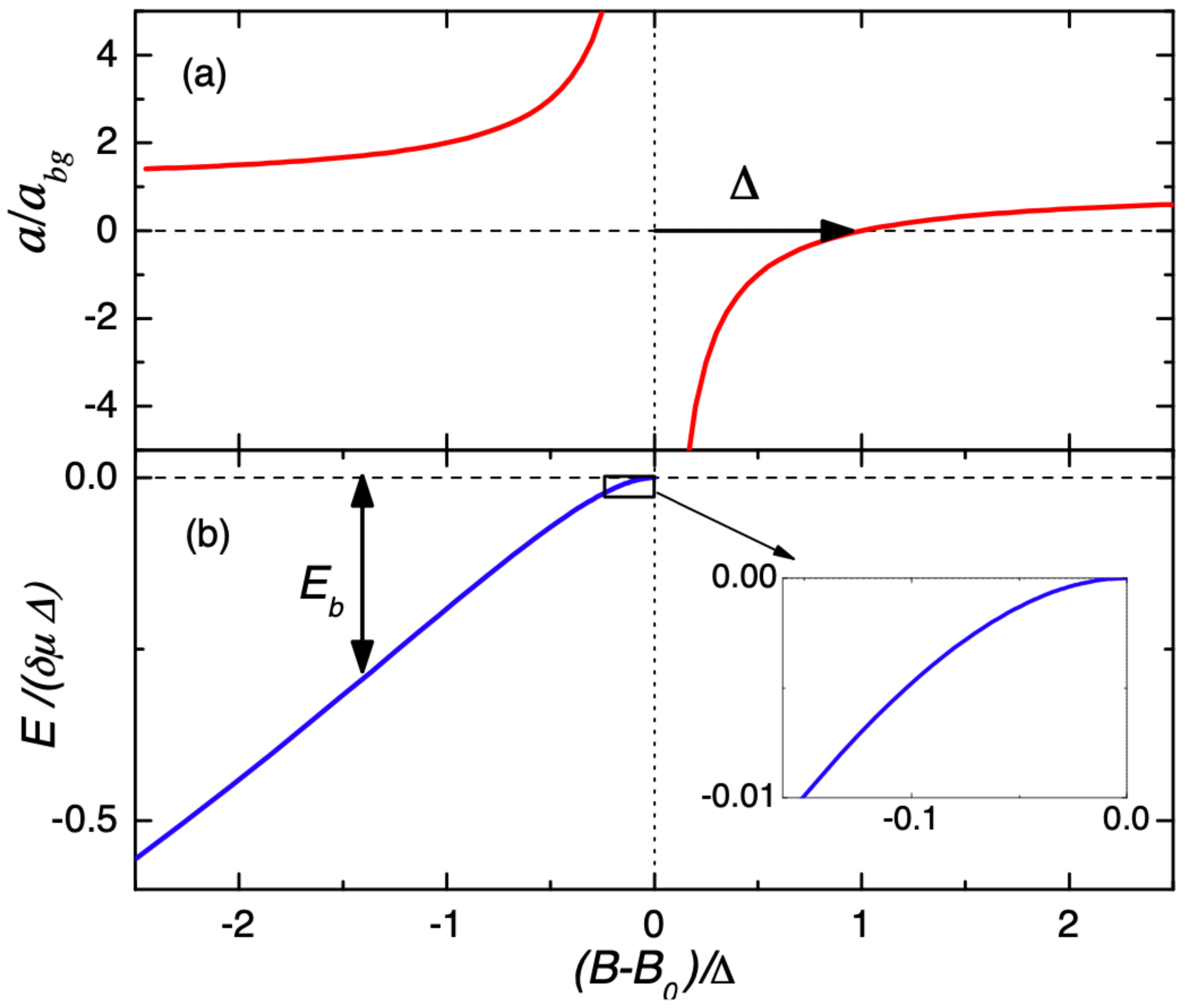

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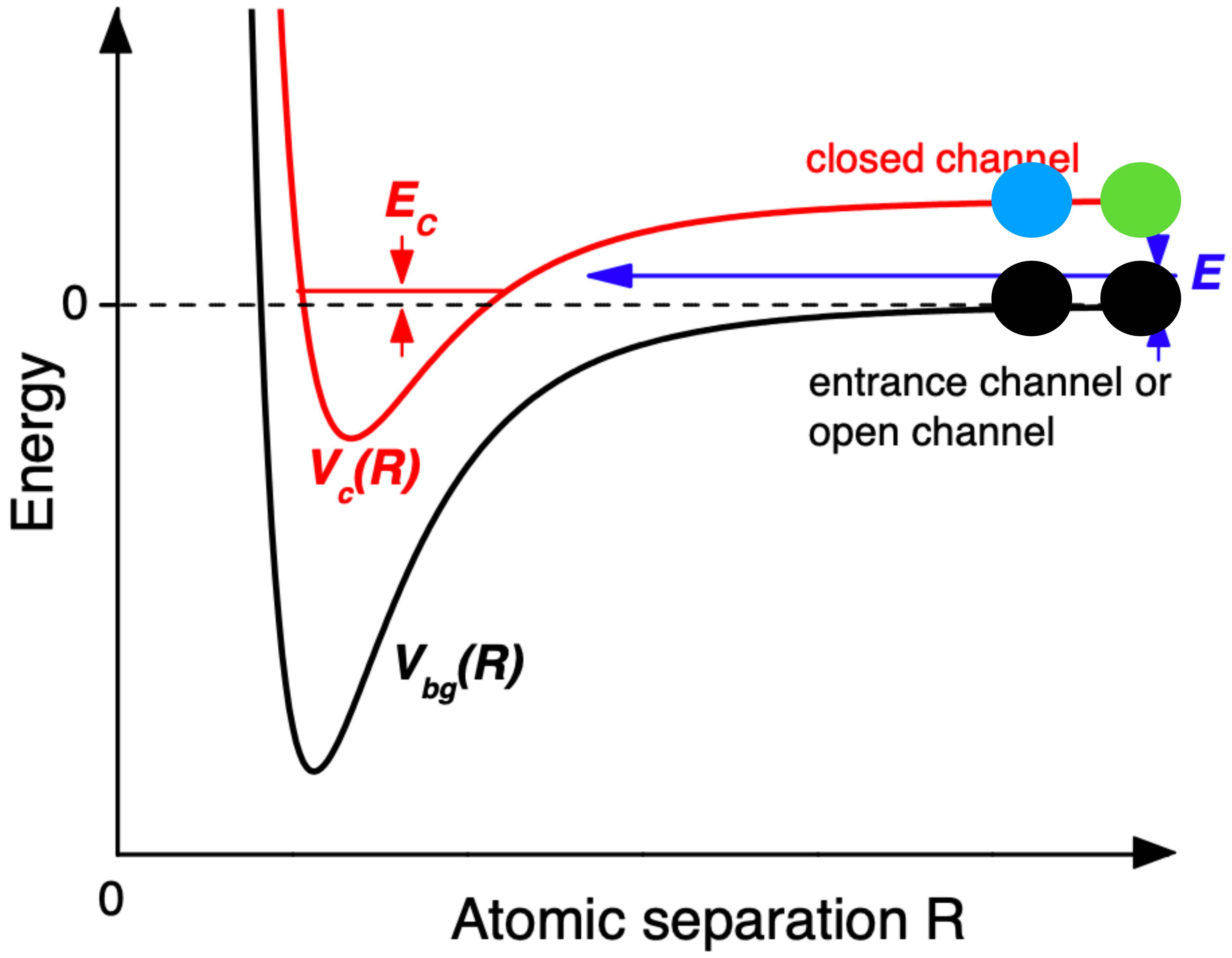

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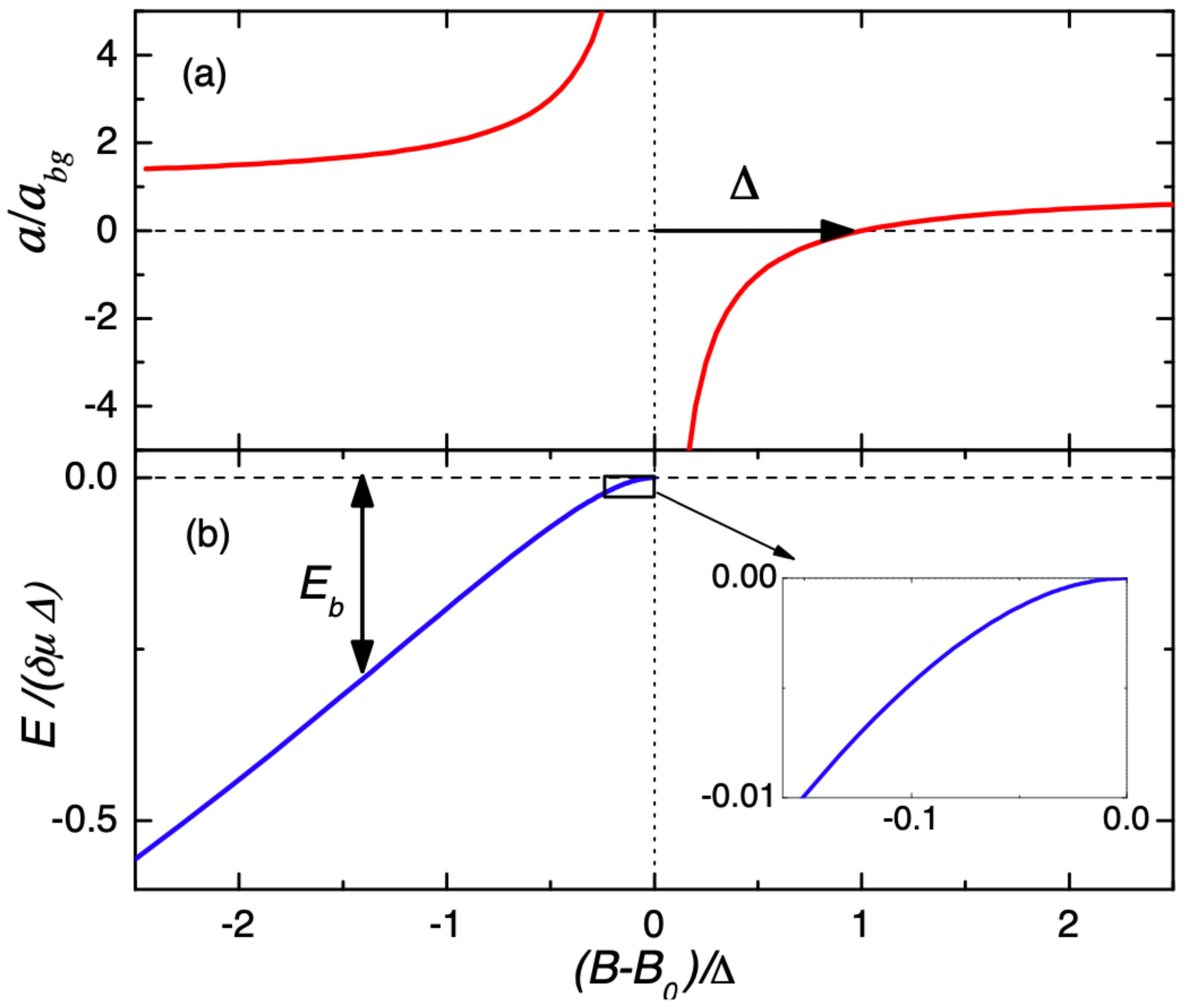

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Scattering length tuning: Feshbach resonance

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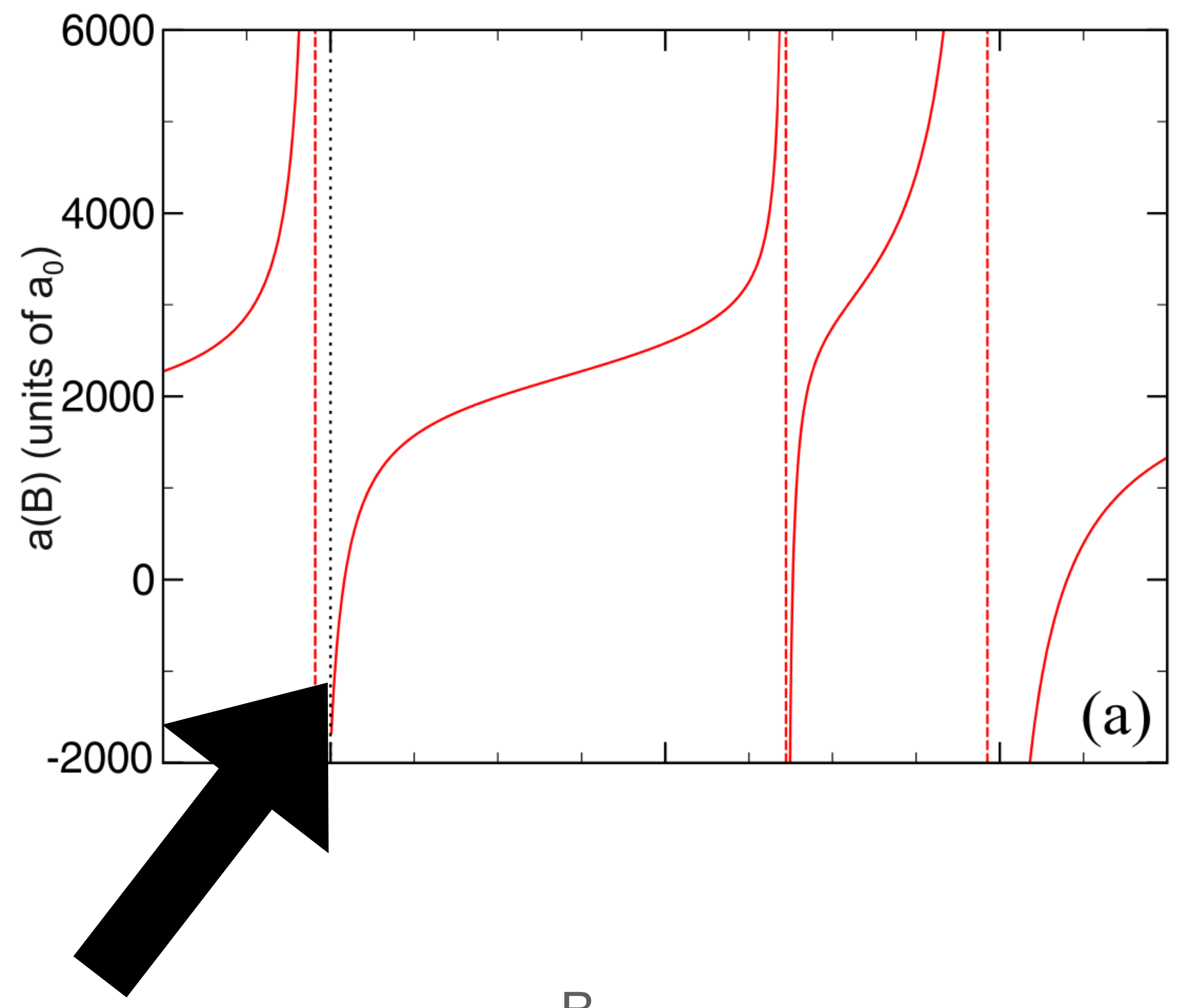
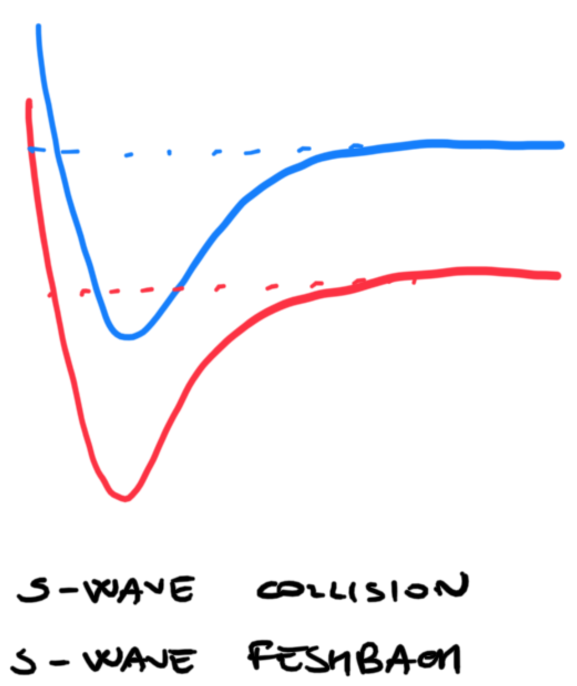
Cesium case
in the lowest
hyperfine state

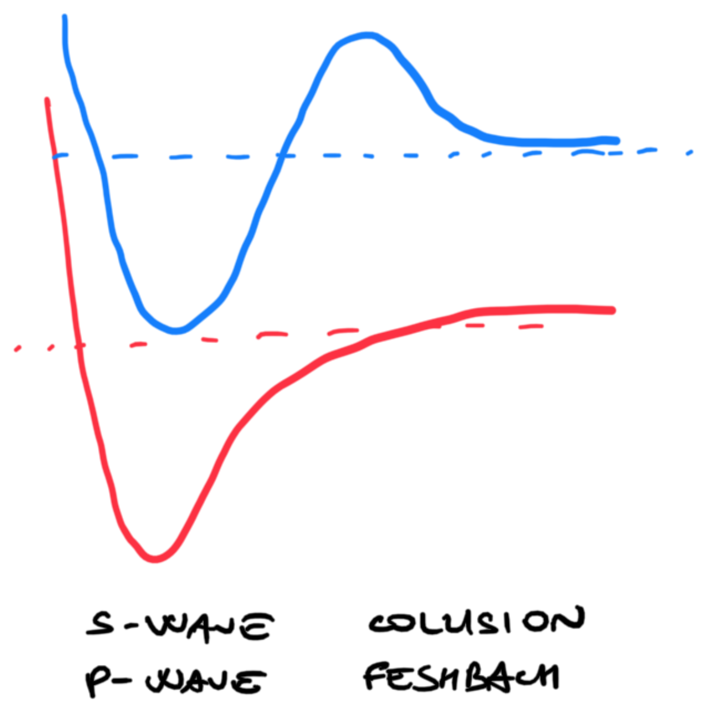


B

B

Considering only closed channels with same angular momentum of the entrance one





Scattering length tuning: Feshbach resonance

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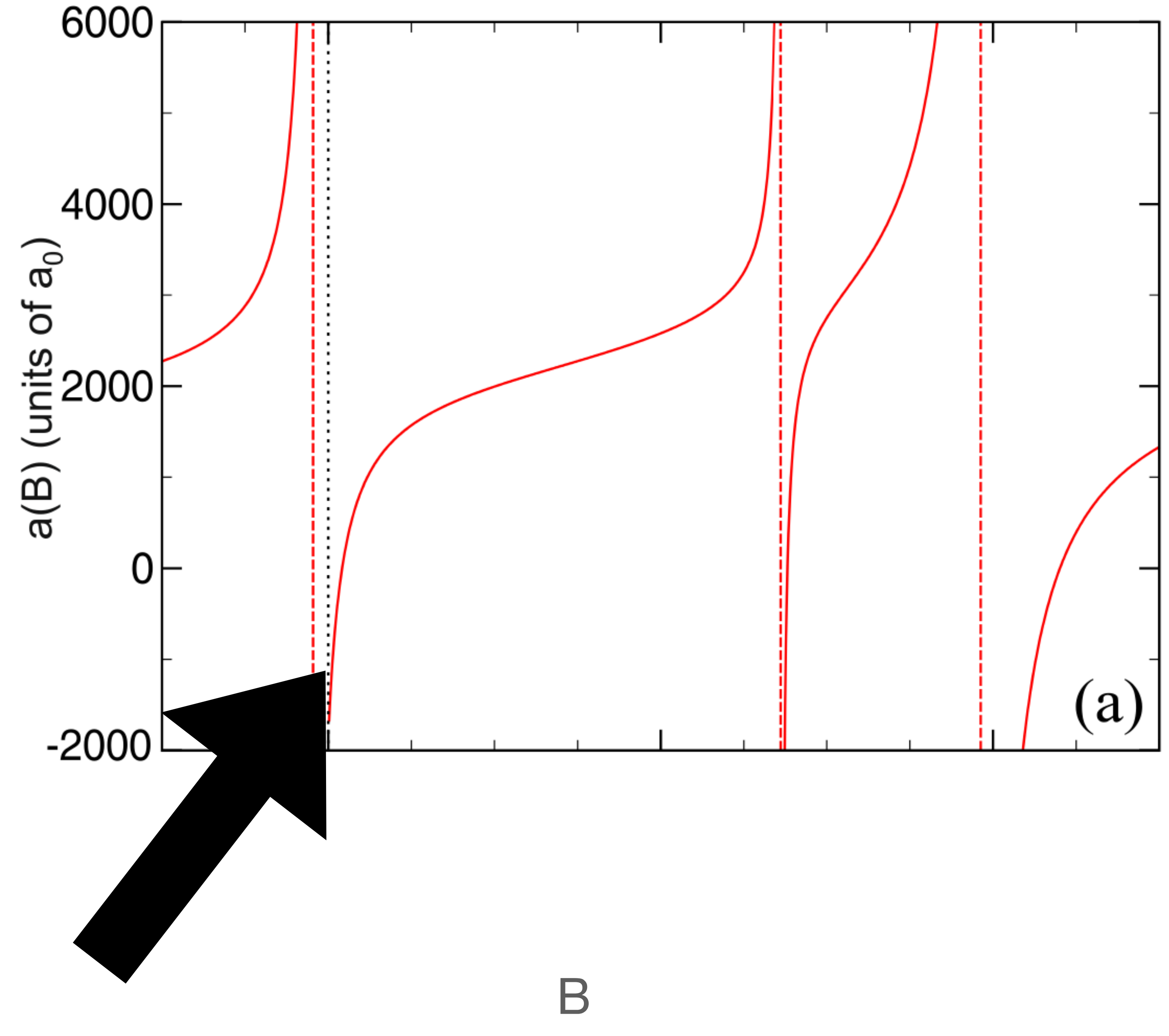
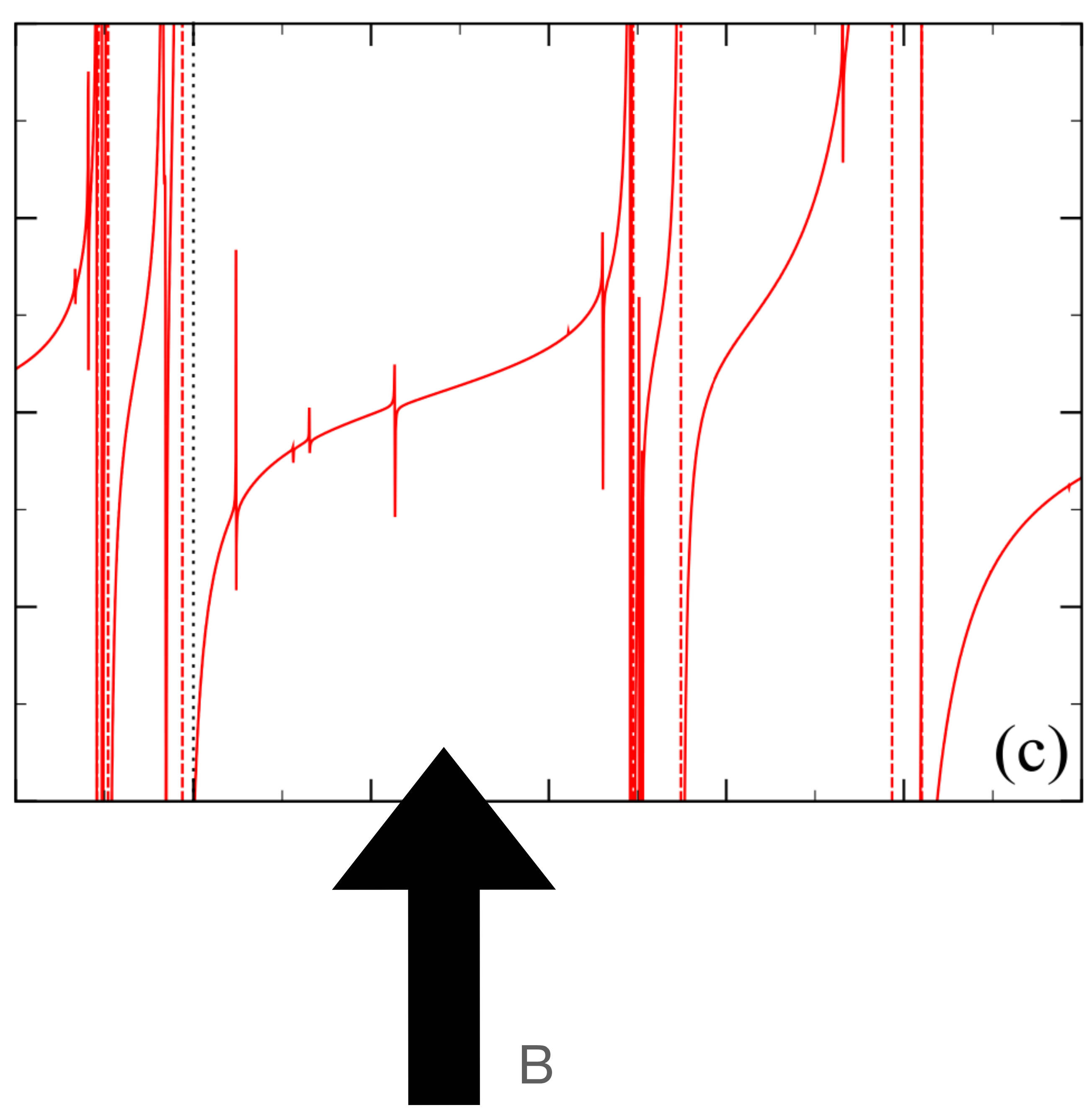
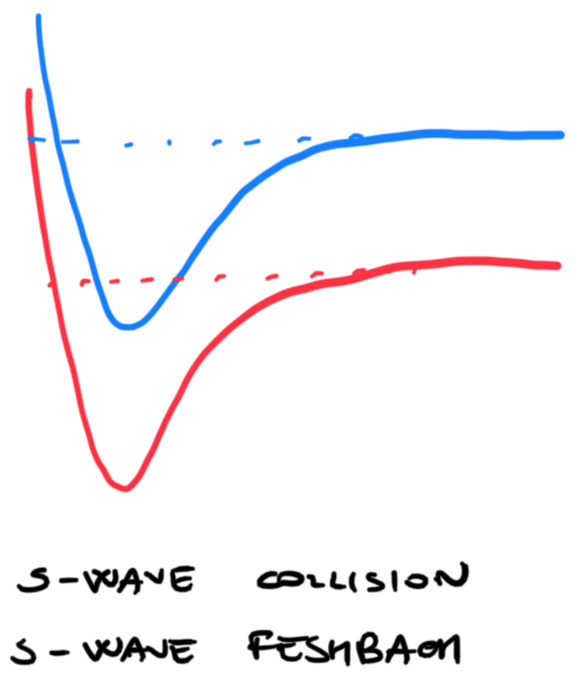
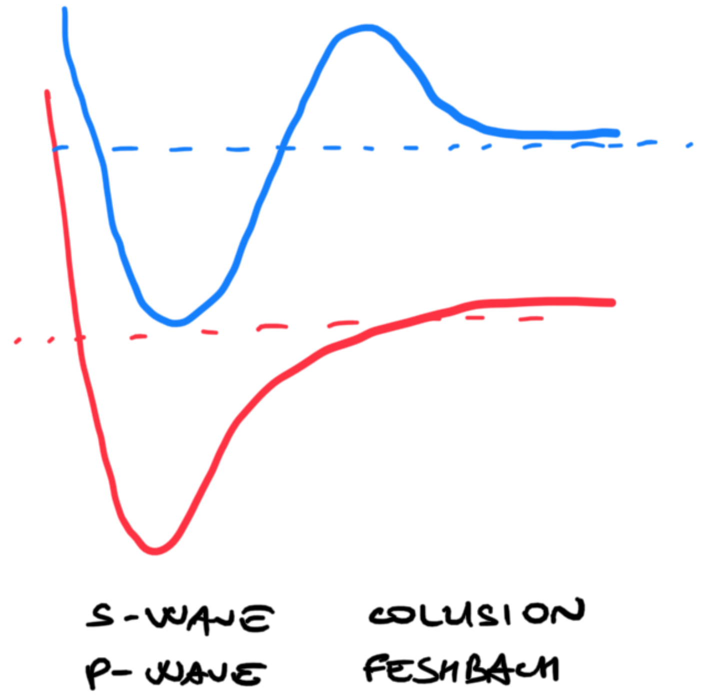




Considering only closed channels with same angular momentum of the entrance one

Considering also closed channels with different angular momentum compared to the entrance one

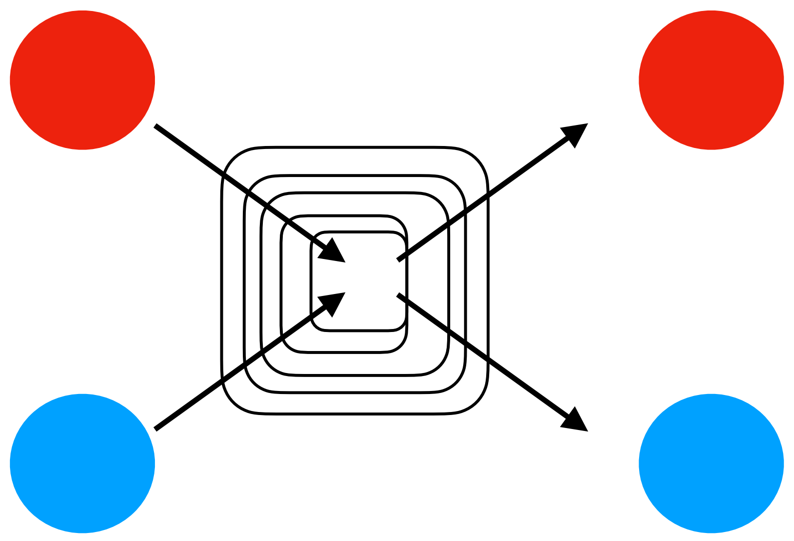




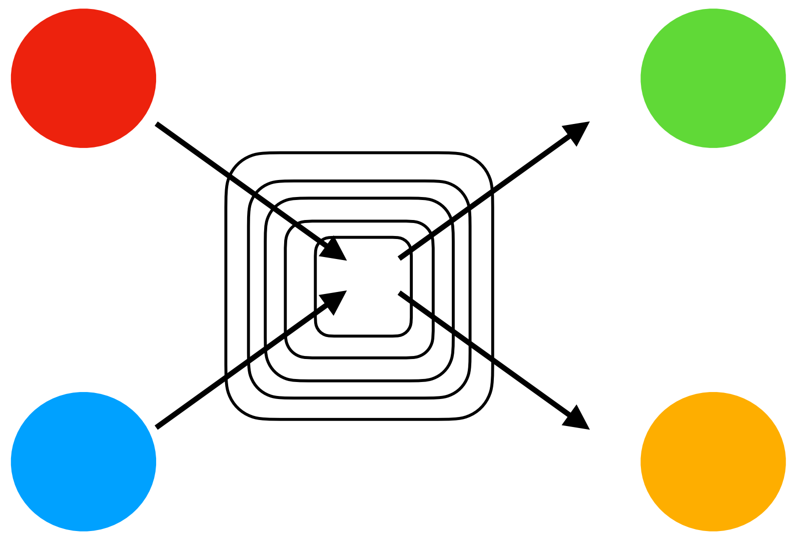
Remember/1: the good and the bad

For each collision there will be:

Elastic collision rate (good for evaporation)
Inelastic collision rate (not necessary bad)



Elastic collision
Energy conserved



Inelastic collision
Internal energy converted to kinetic energy (or viceversa)

Remember/2: Fermions

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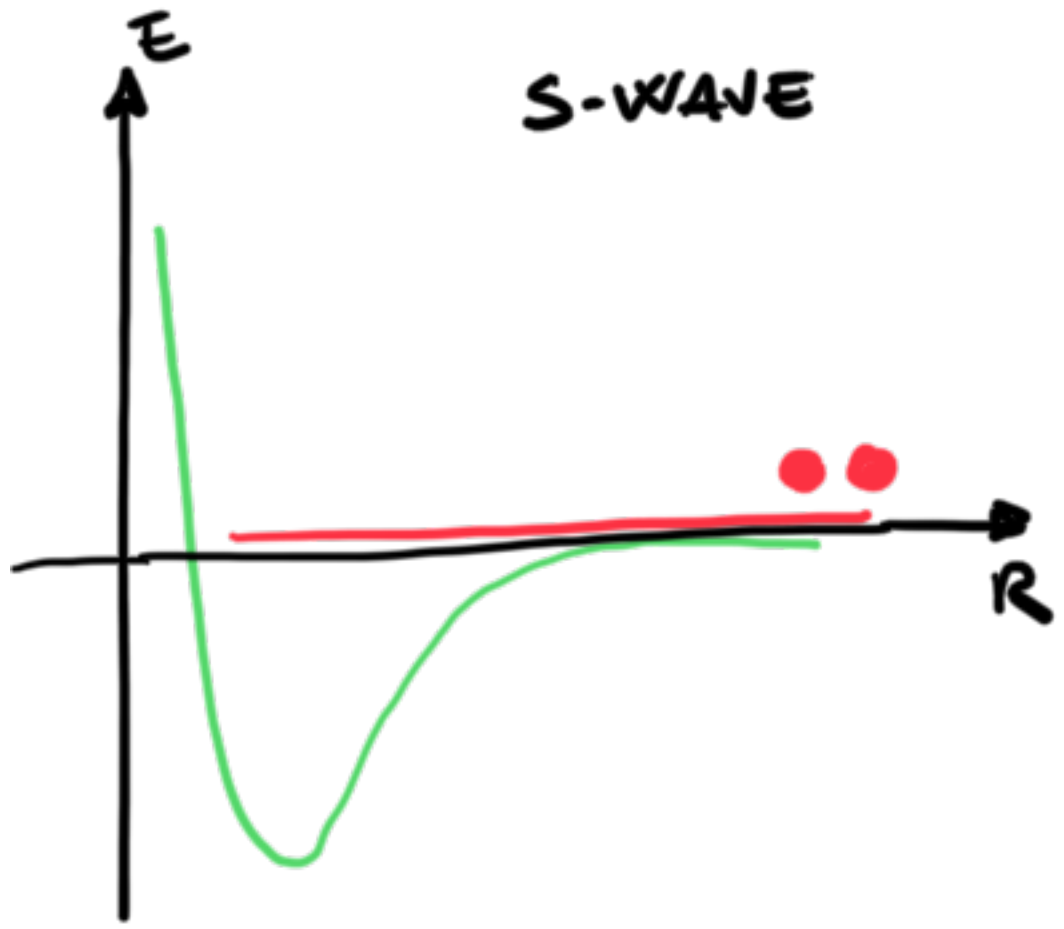

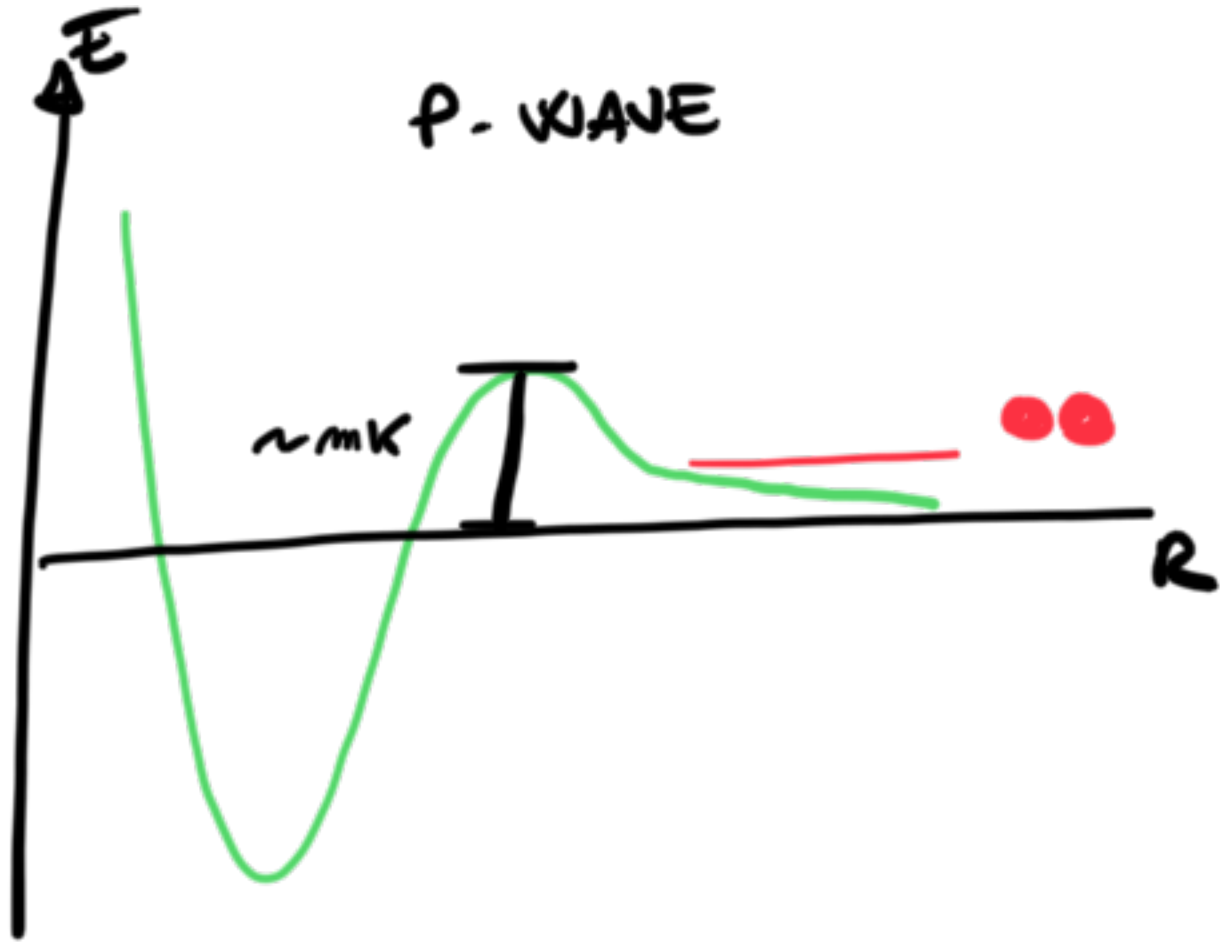

Remember/2: Fermions

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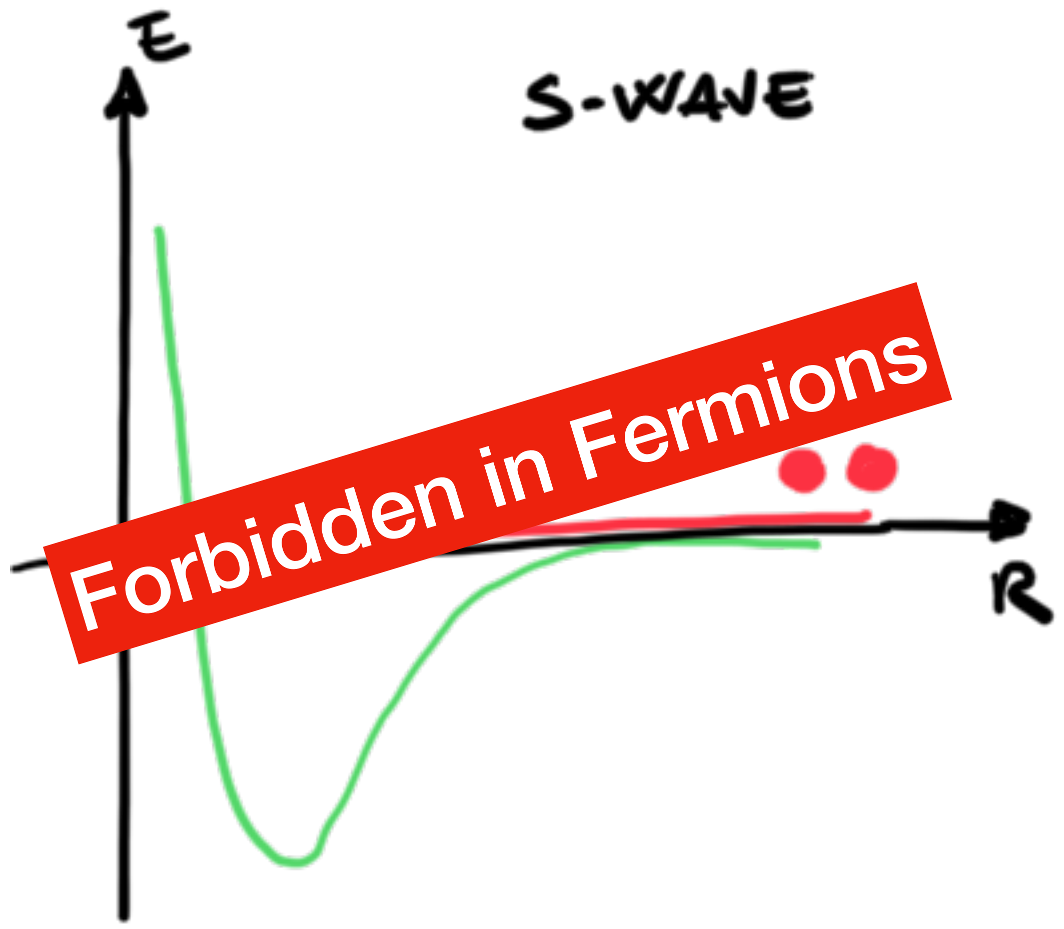

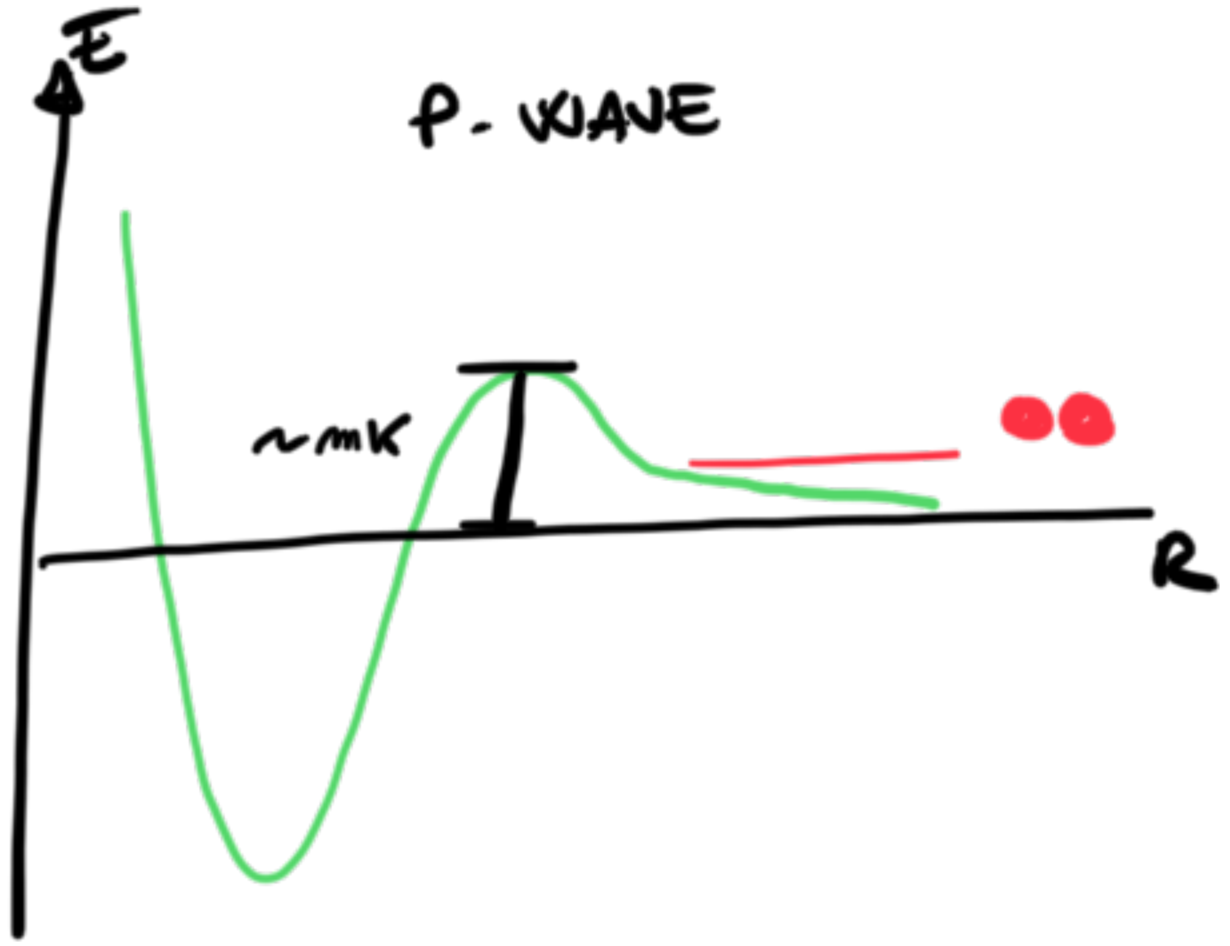

Remember/2: Fermions

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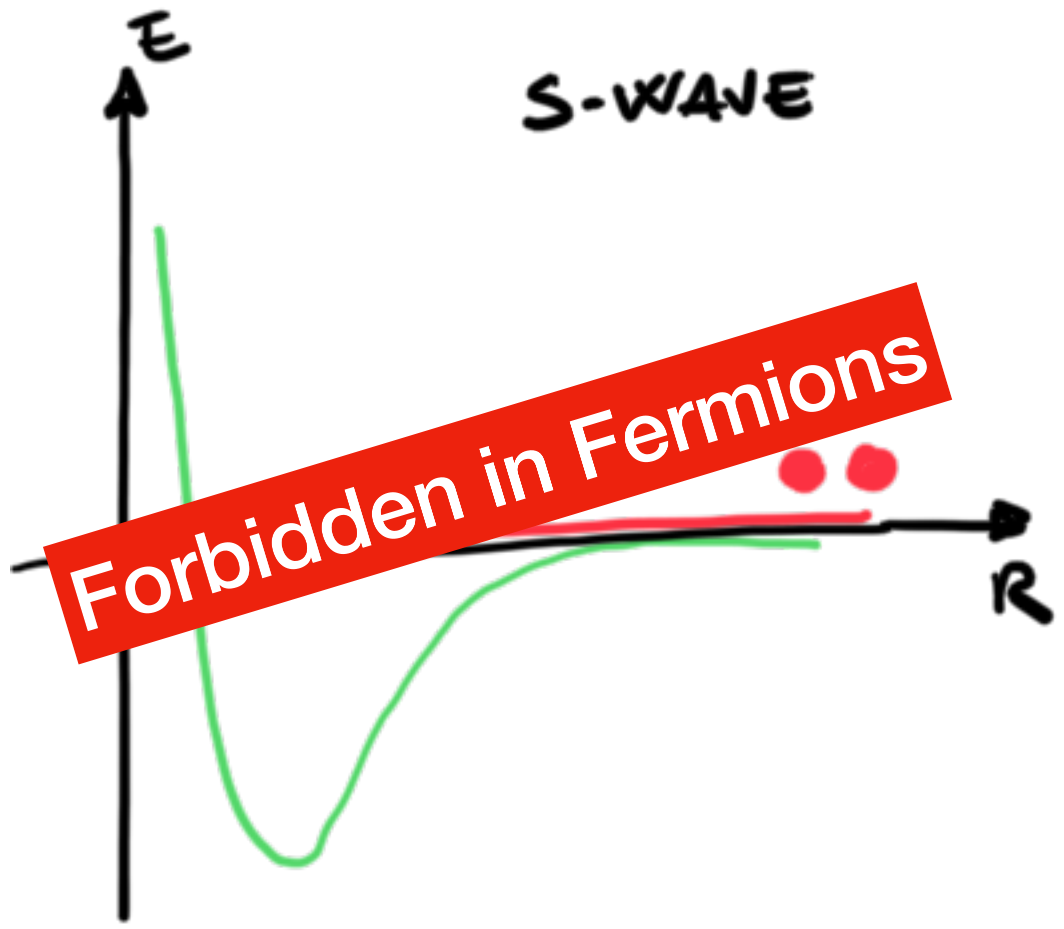

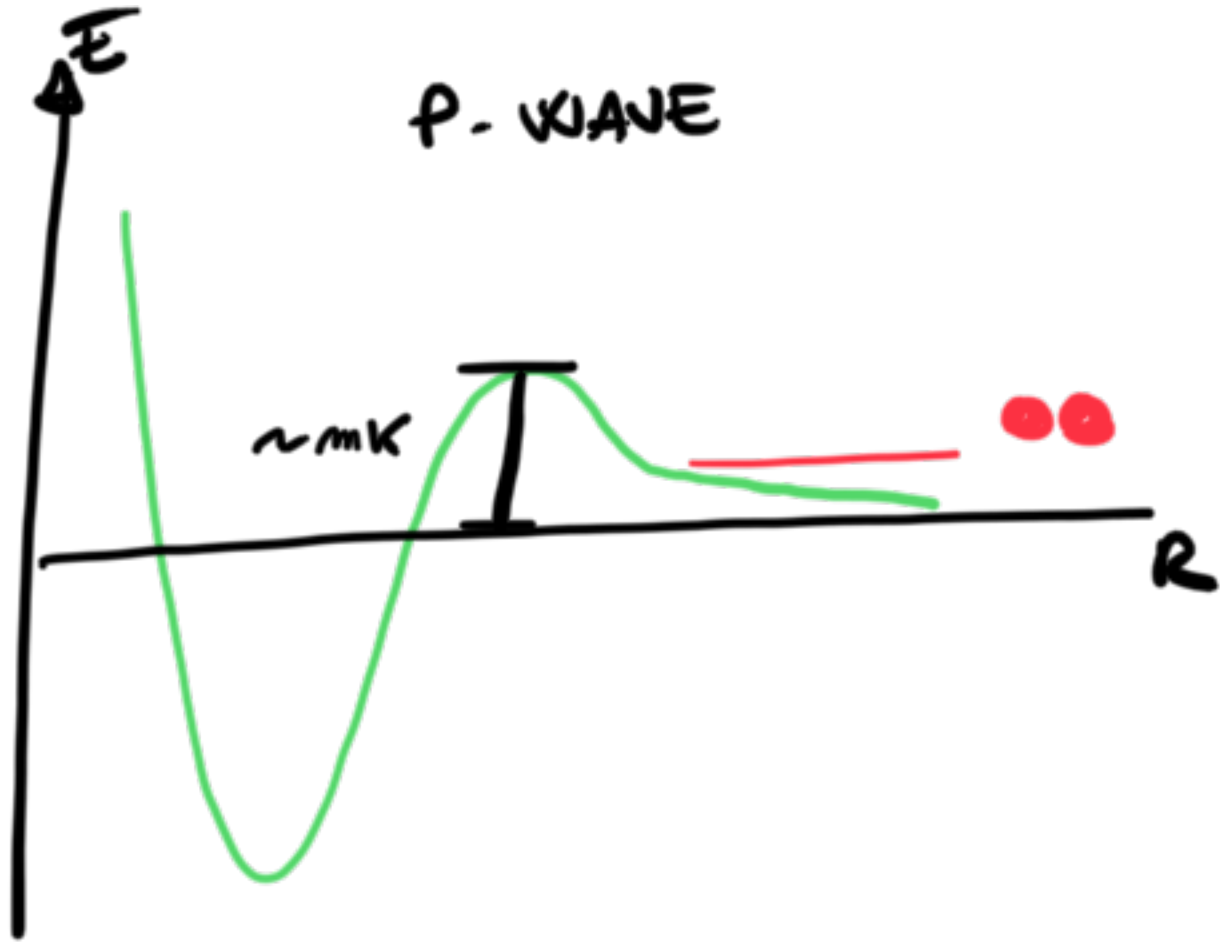

Identical Fermions do not come enough close to see each other below some temperature: No collisions, no termalization

Remember/2: Fermions

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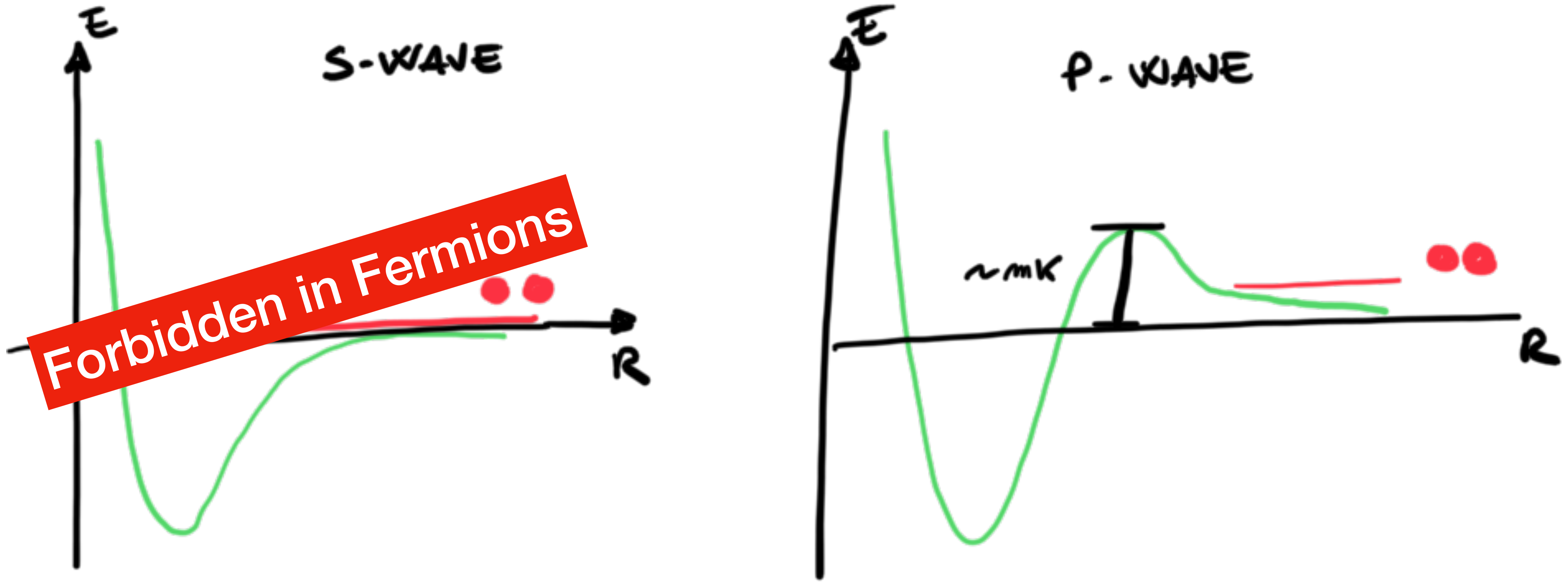

Identical Fermions do not come enough
close to see each other below some temperature:
No collisions, no termalization

Mixture of distinguishable fermion or together with a boson to allow evaporation

There is even more about collisions

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- Scattering in pancakes and cigars (see Laurianne lecture)
- Dipolar gases (see Francesca lecture):
  - beyond van der Waals interactions: Magnetic and electric dipoles
- Rydberg atoms (see Hannes lecture):
- Interactions between
  - a neutral atom and an ion
  - ground state atom and a Rydberg atoms

0

$1+1$

3

$\ldots$

$1+1$

Atomic spectra

0

1+1

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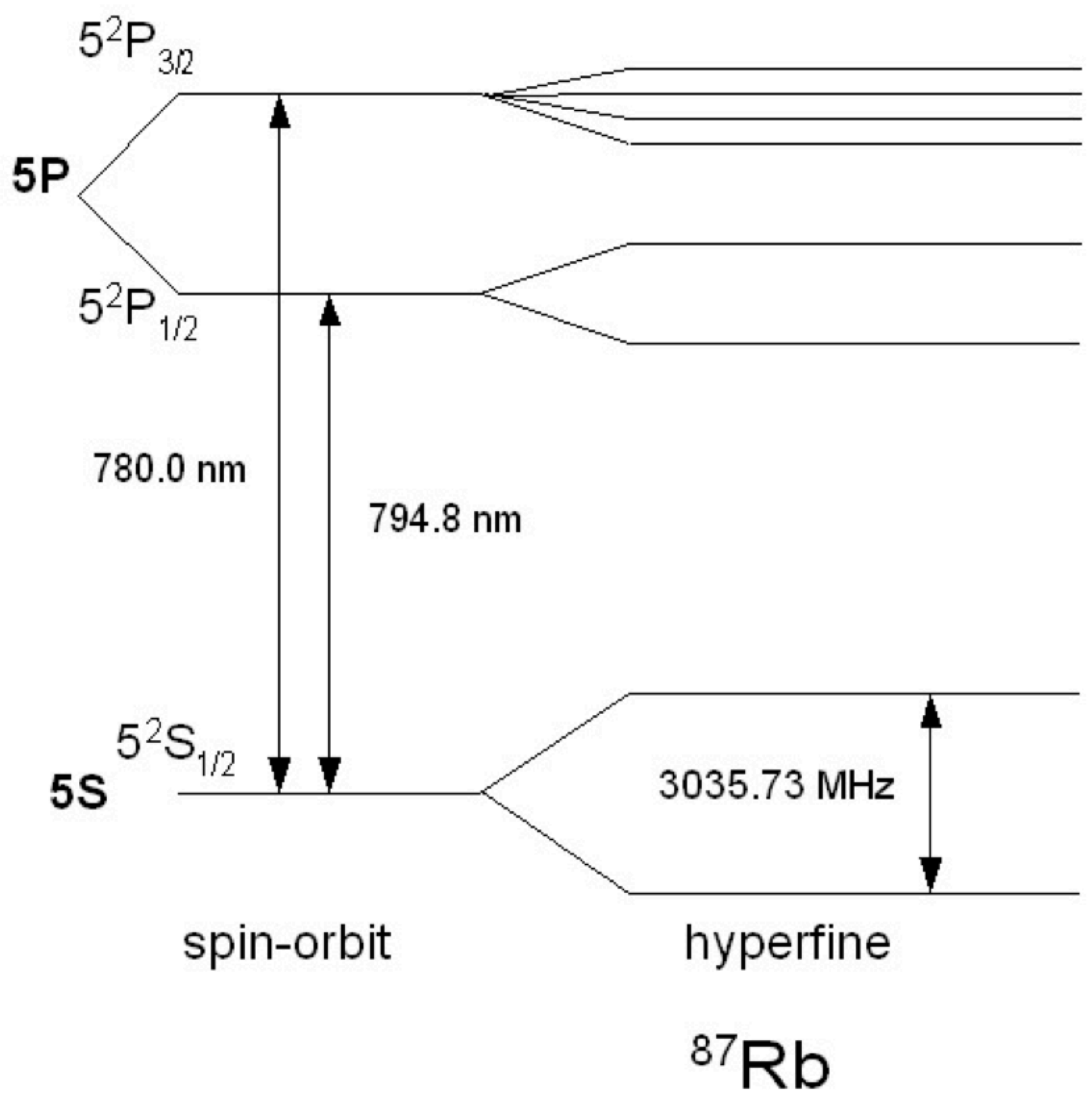
Alkali



Atomic spectra

0

1+1

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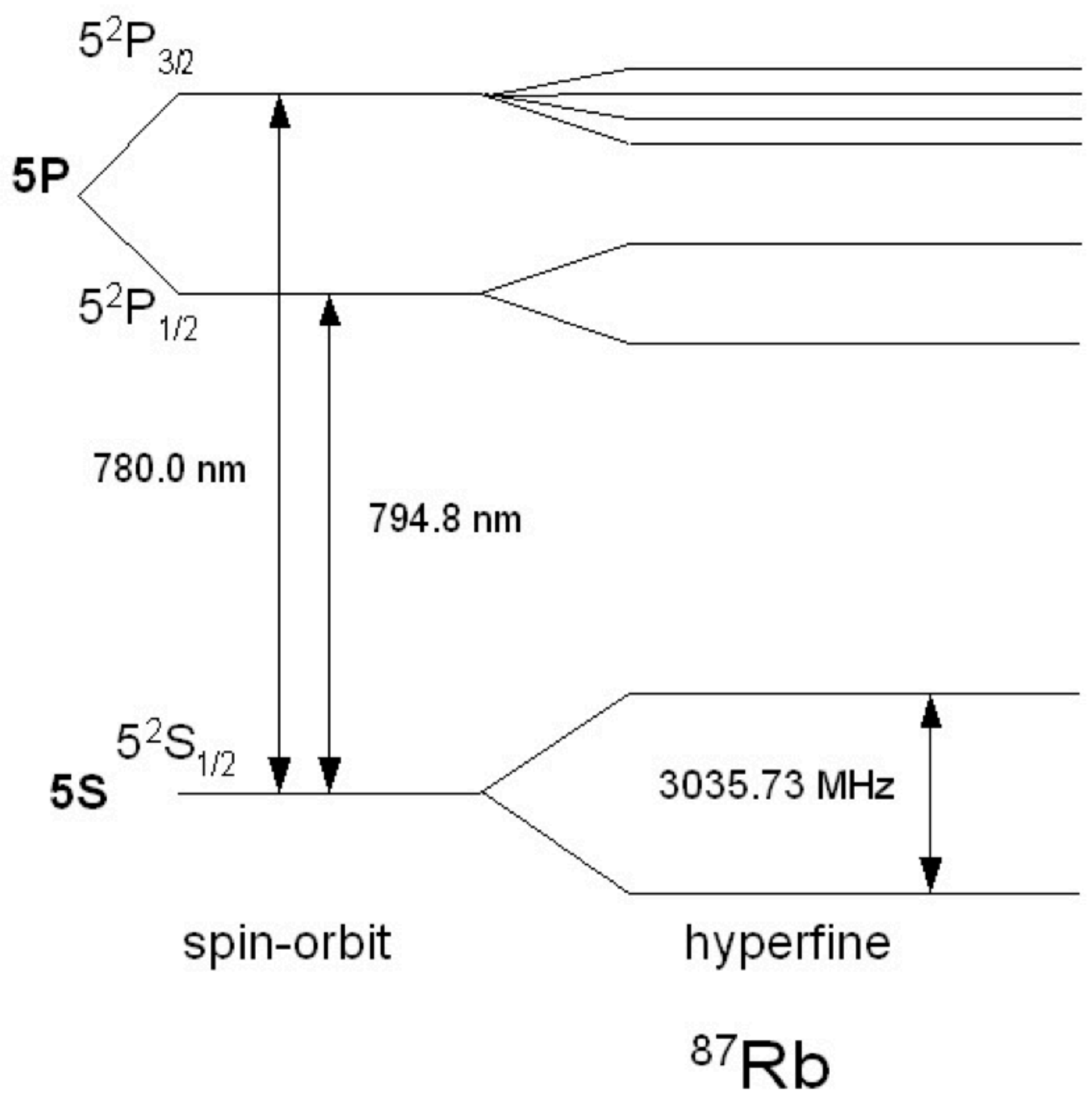
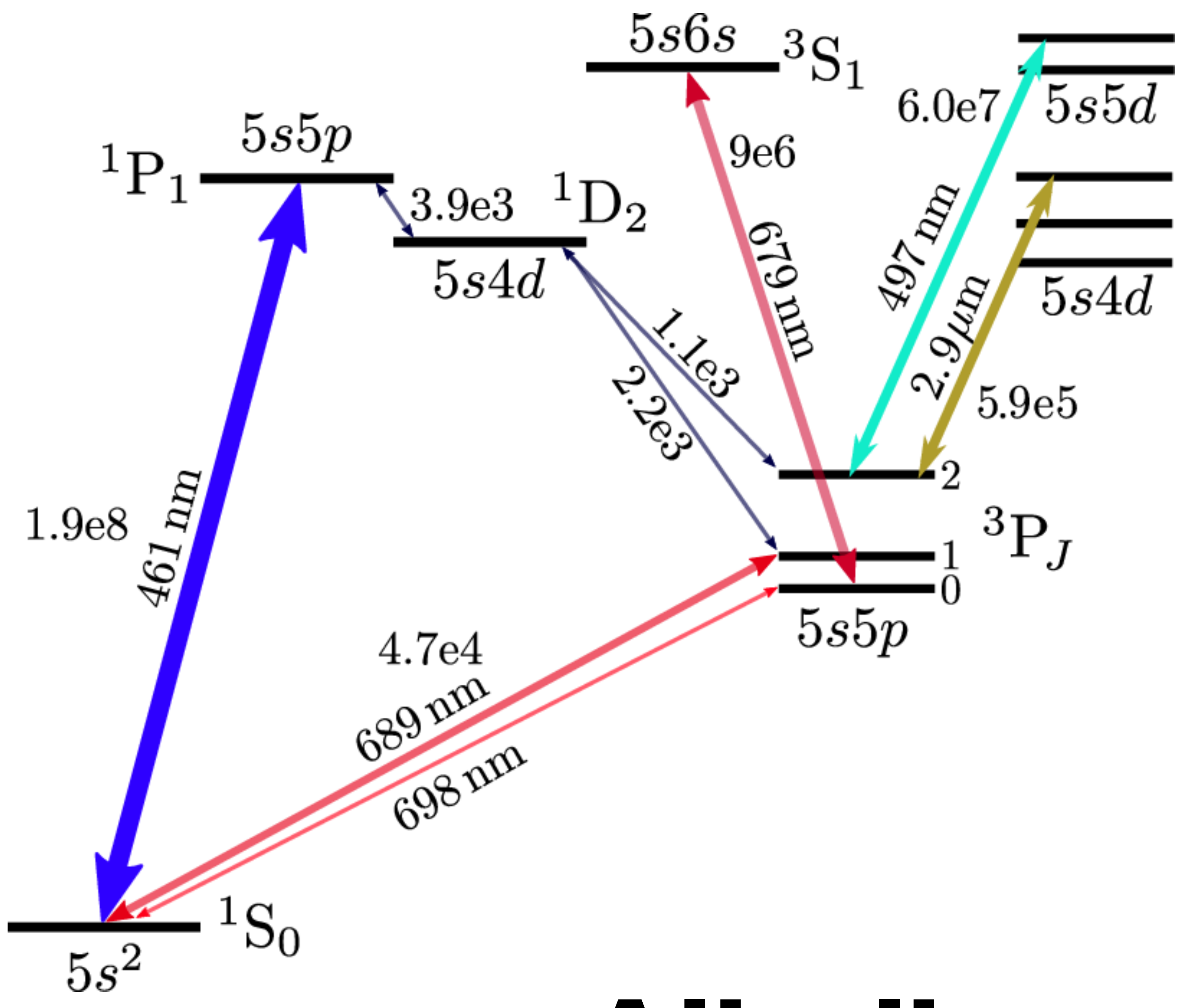
Alkali





Alkali-earth

Atomic spectra

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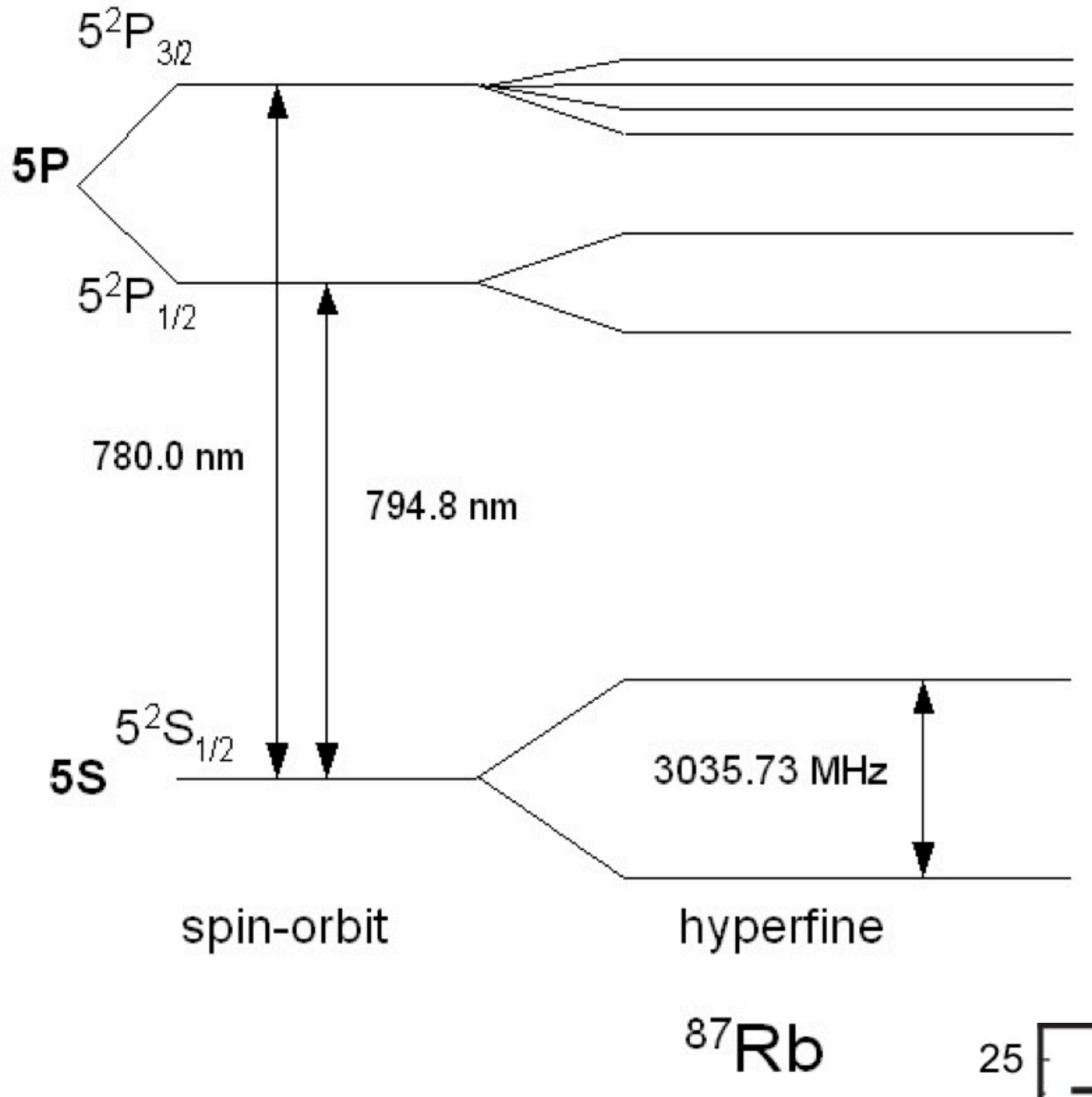
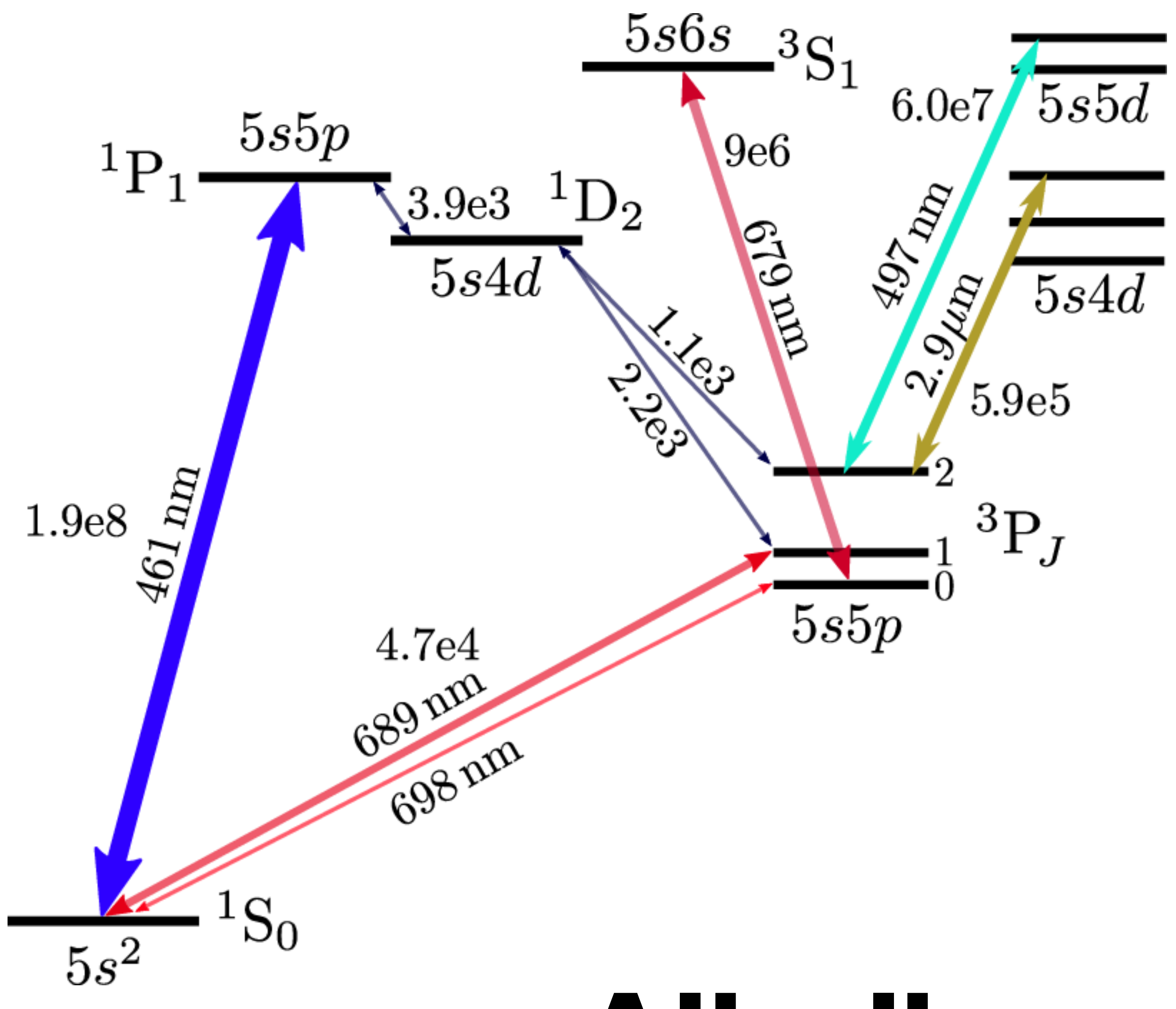
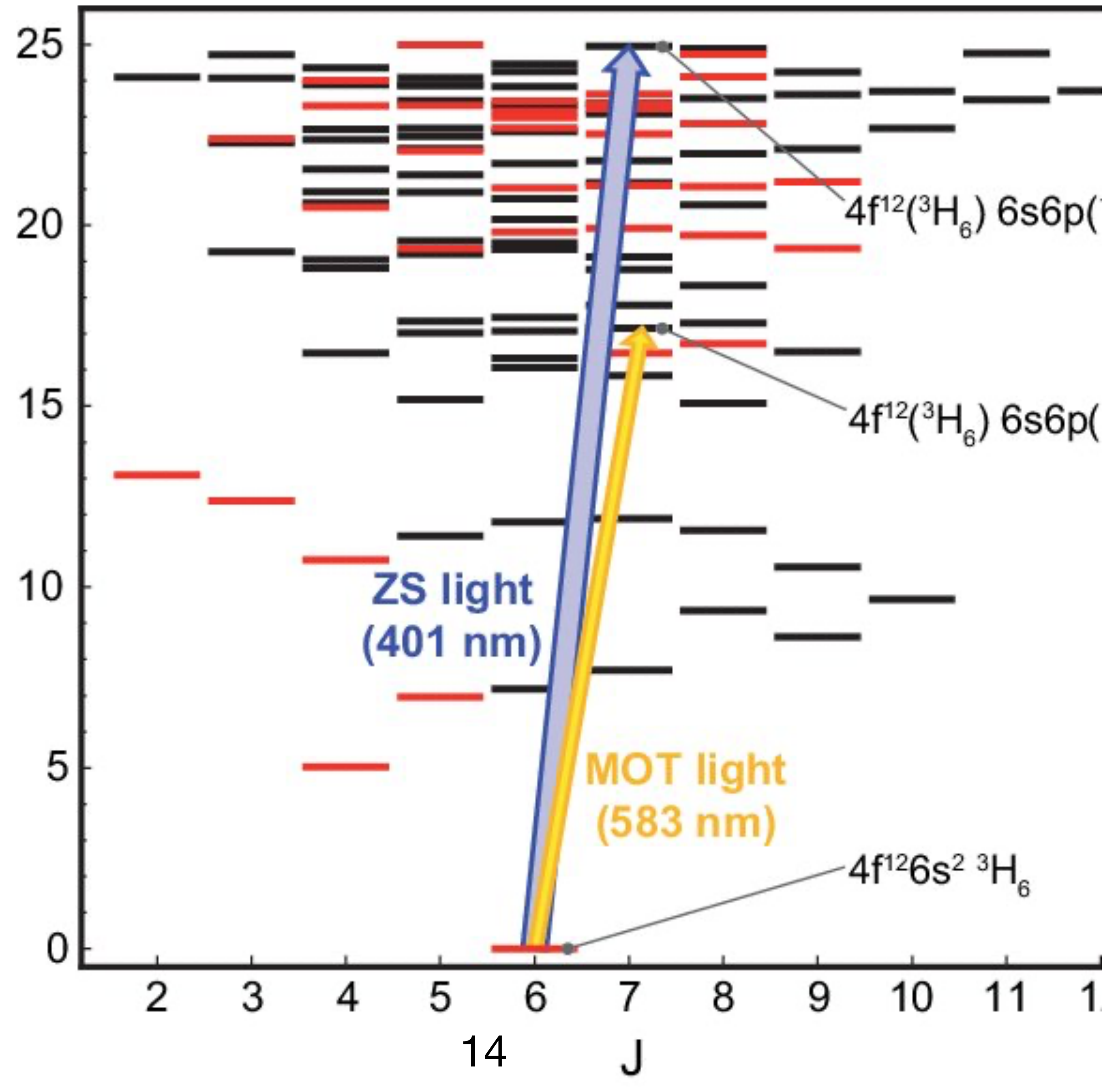
Alkali





Alkali-earth

Lantanides



A diatomic molecule is an atom too many
Arthur Leonard Schawlow

0

1+1

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Electronically excited state

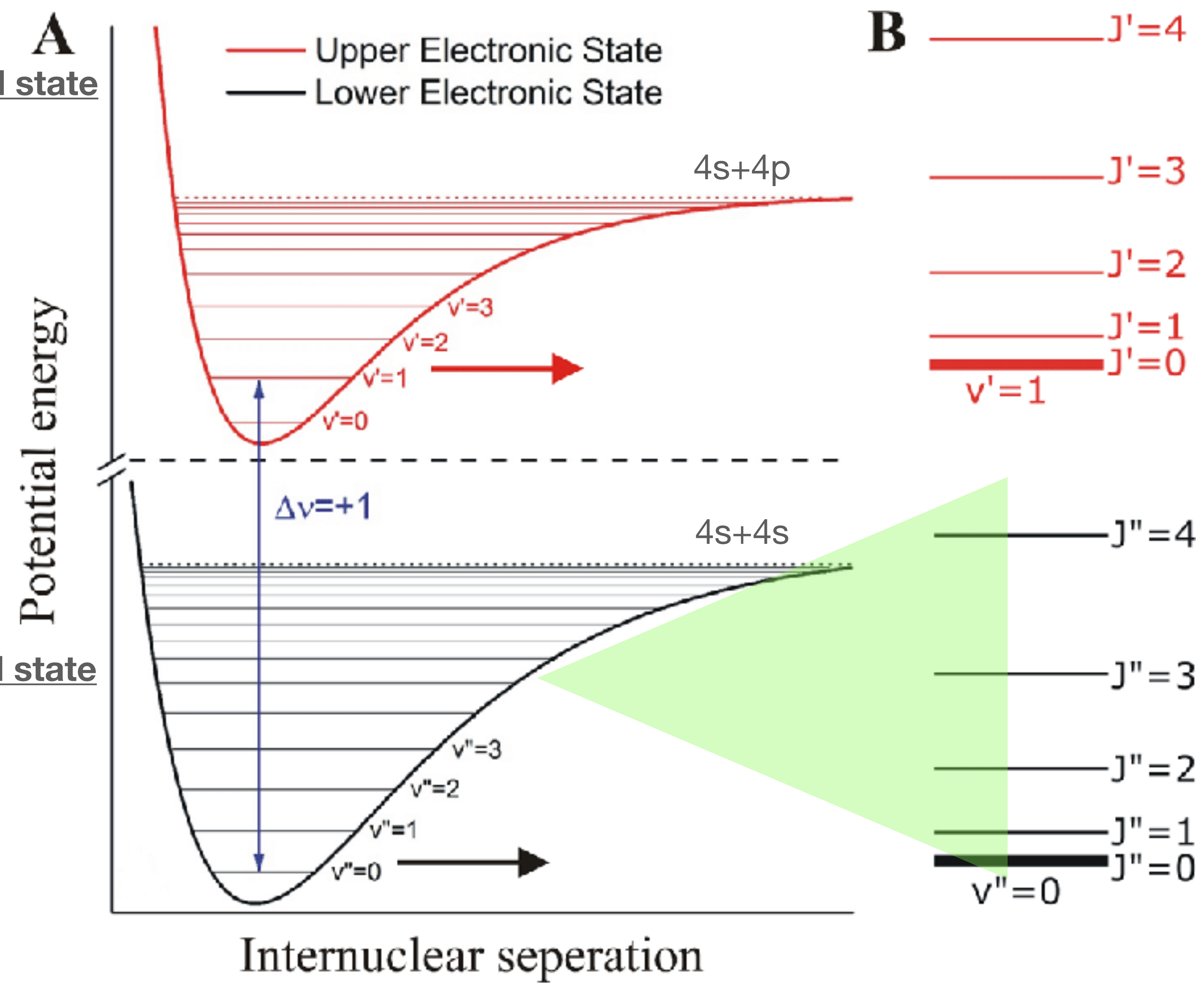
Singlet+Triplet
L=1

4 Potential

Electronically ground state

Singlet+Triplet
L=0

2 potential



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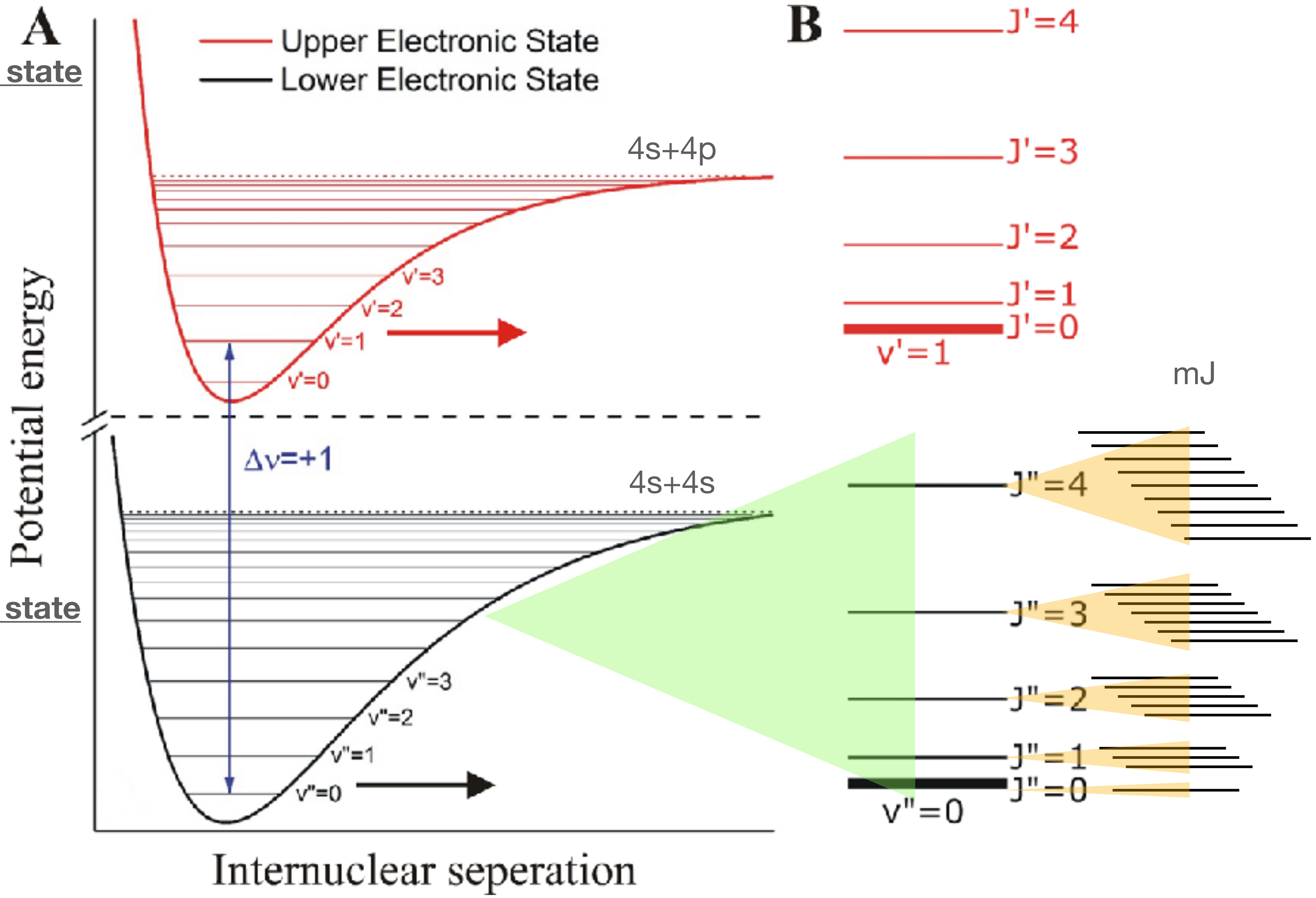

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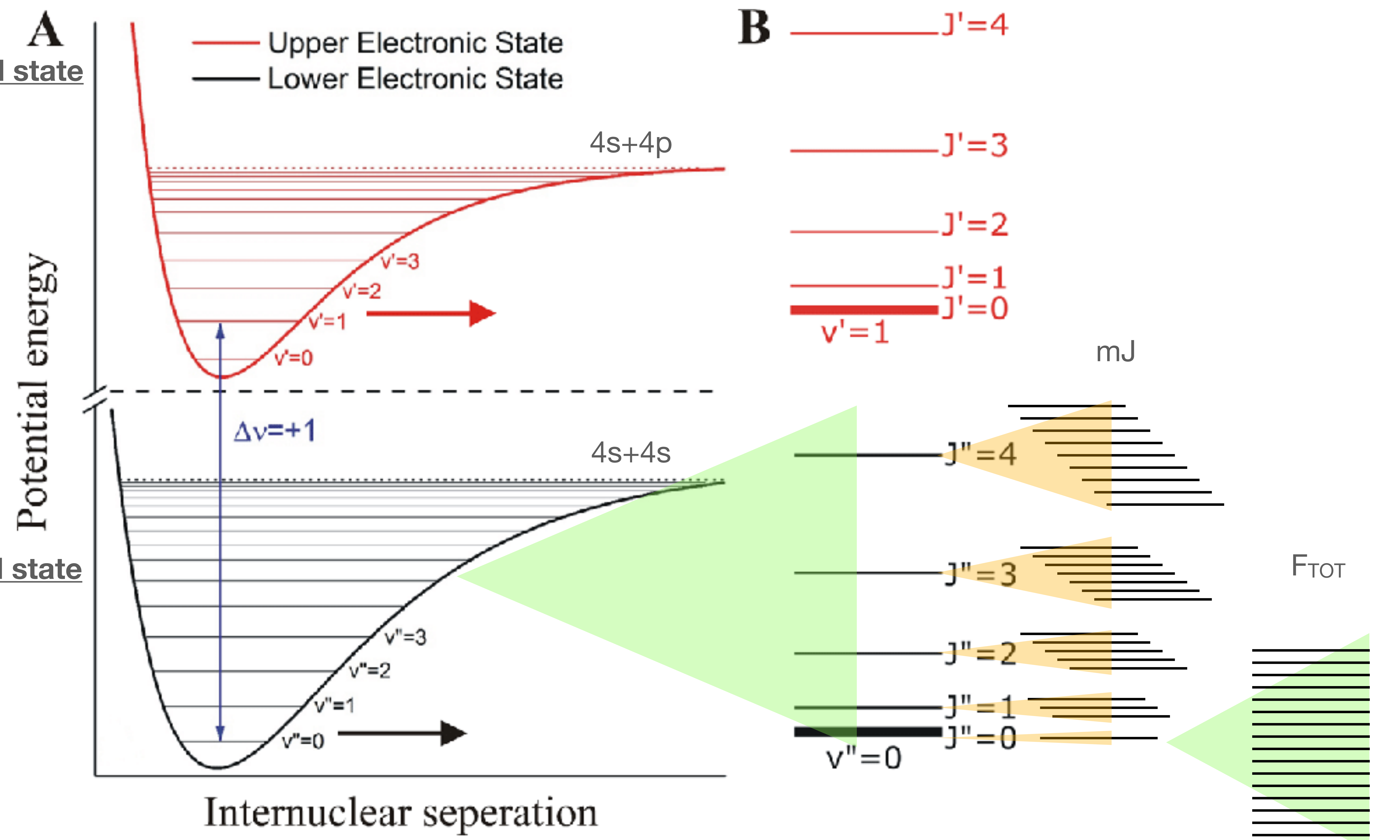

+ couplings

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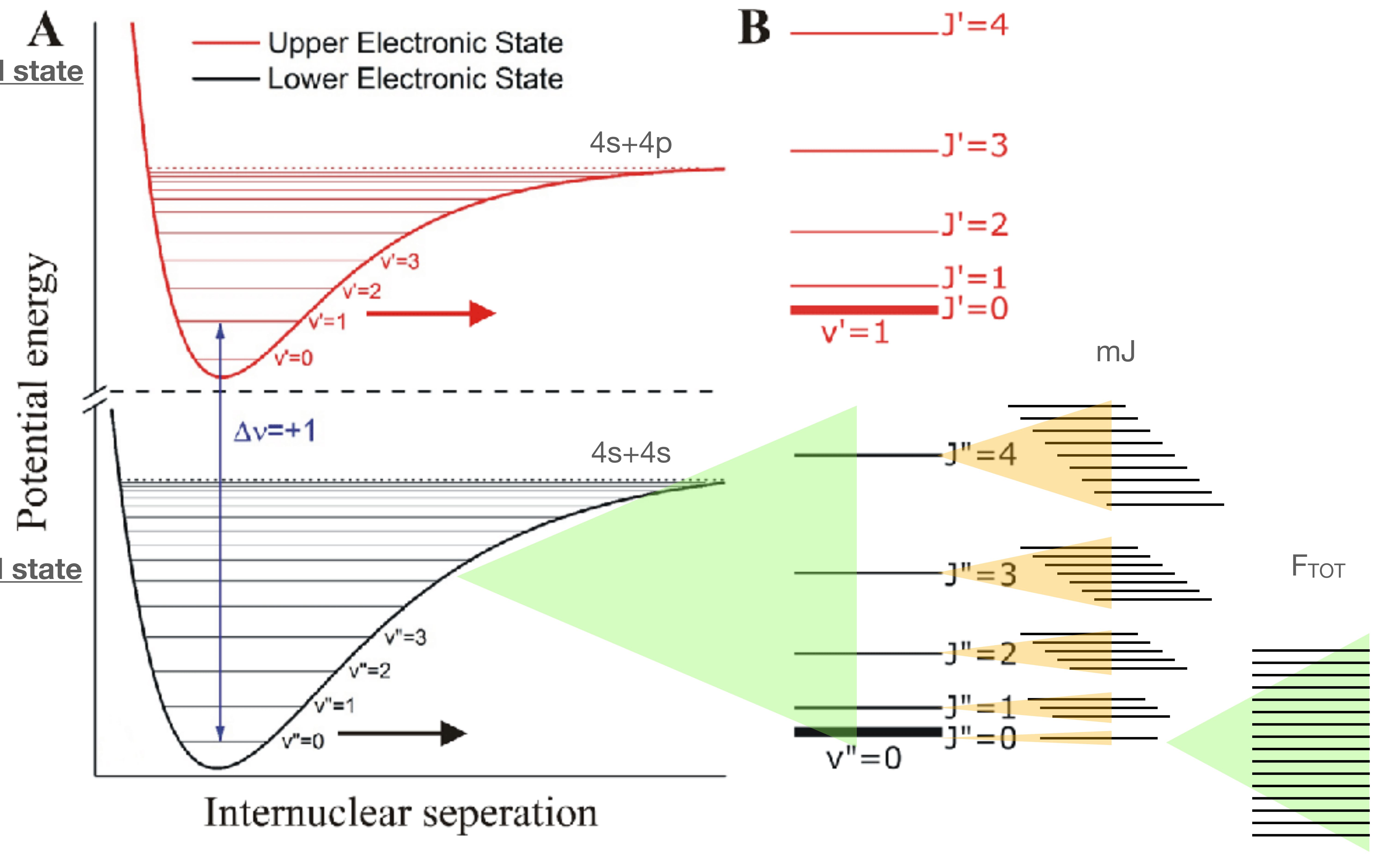

+ couplings

- No closed transition for laser cooling

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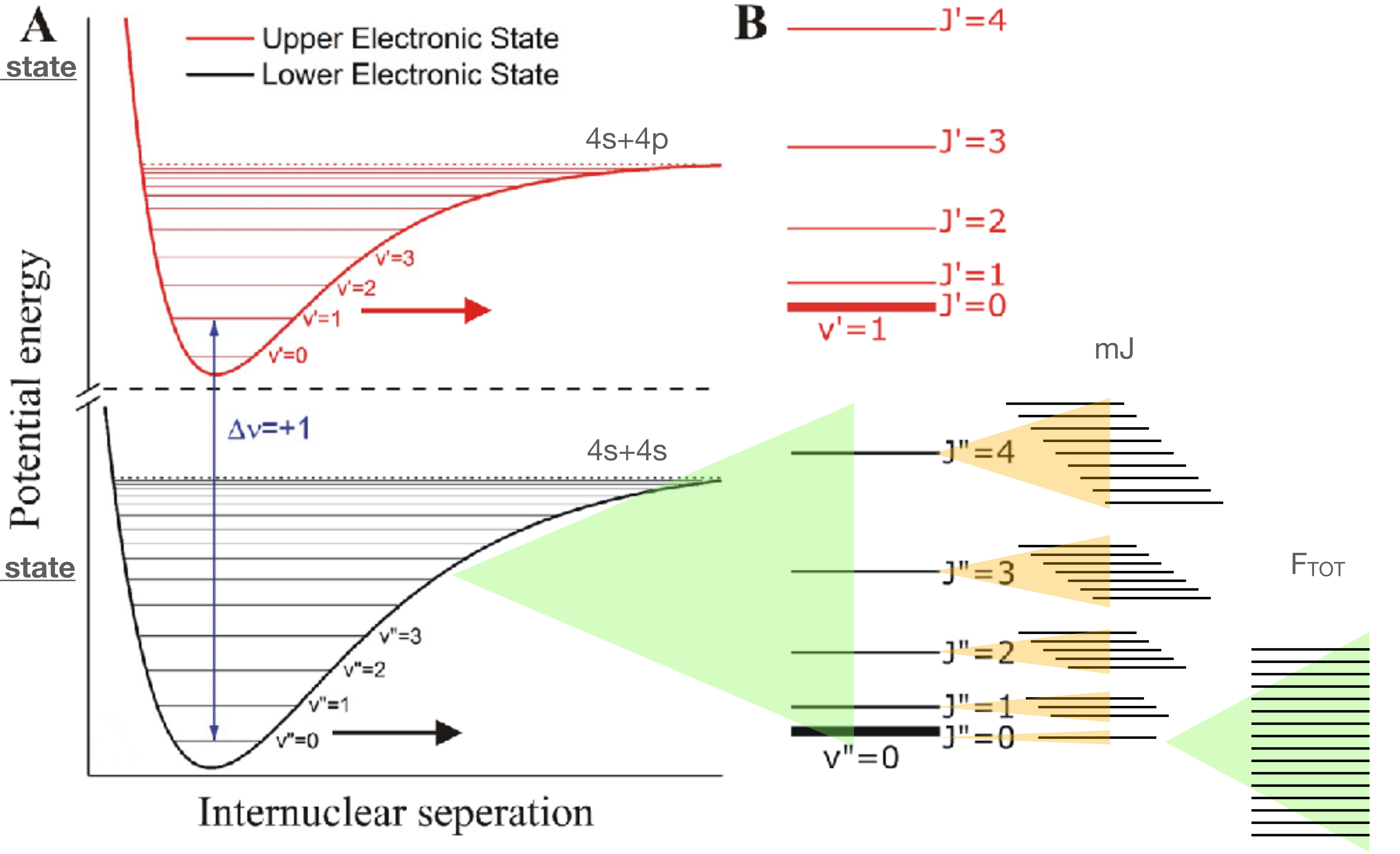
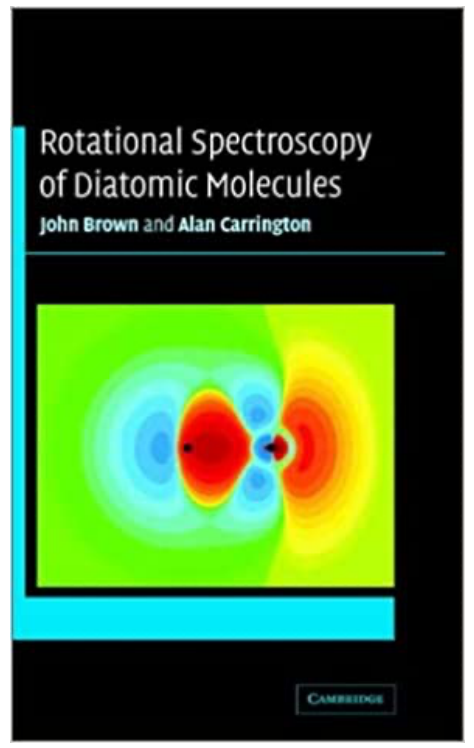
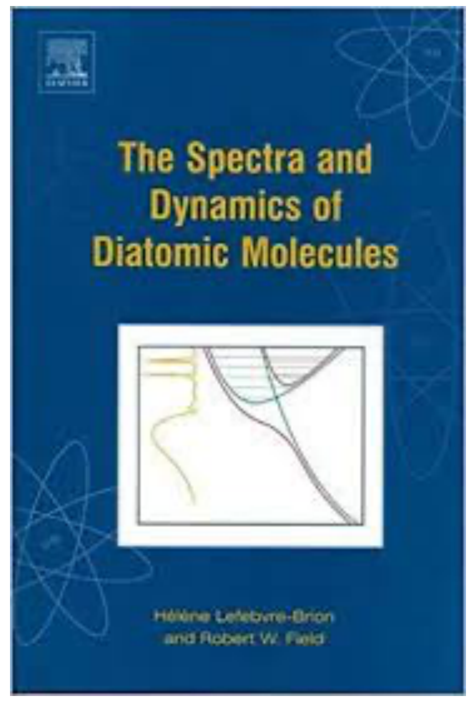




1000 pages each



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- No closed transition for laser cooling

Cooling atoms and glueing

0

1+1

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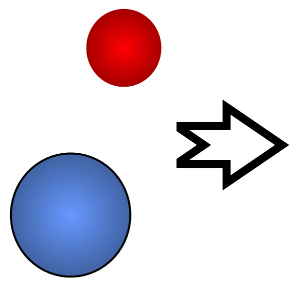
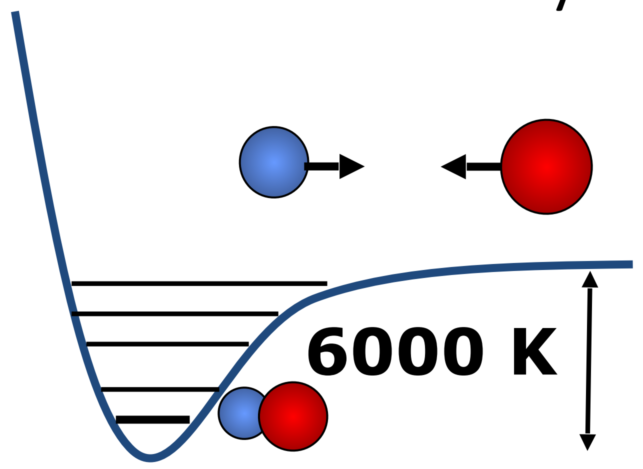
Cooling



Chemistry



Advantage: Start ultracold (@ few hundred nK).

Challenge: Stay ultracold.

Cooling atoms and glueing

0

1+1

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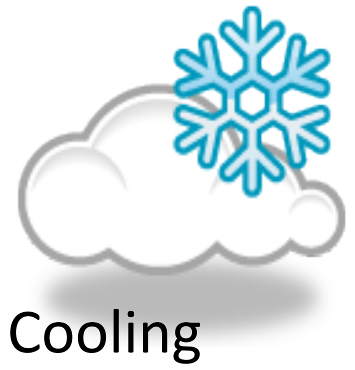
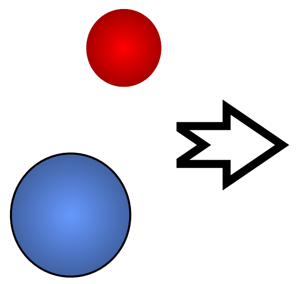


Cooling



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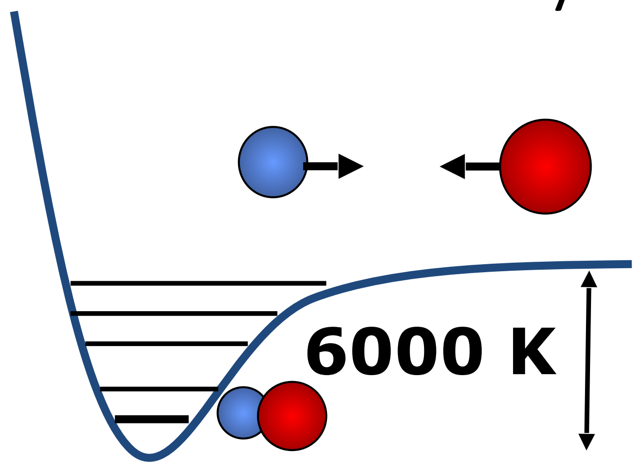

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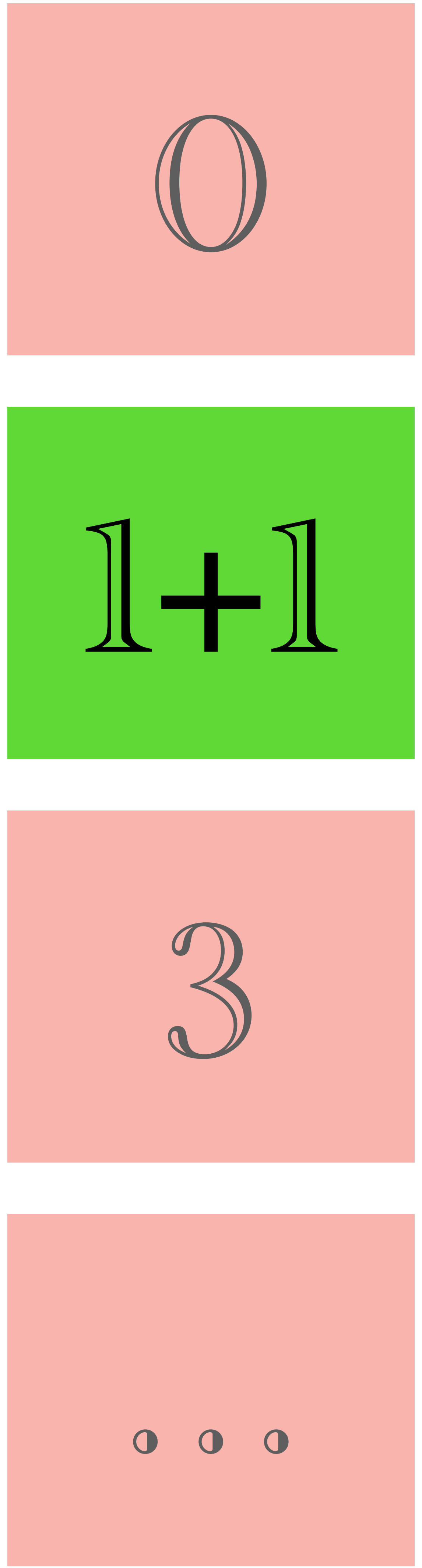
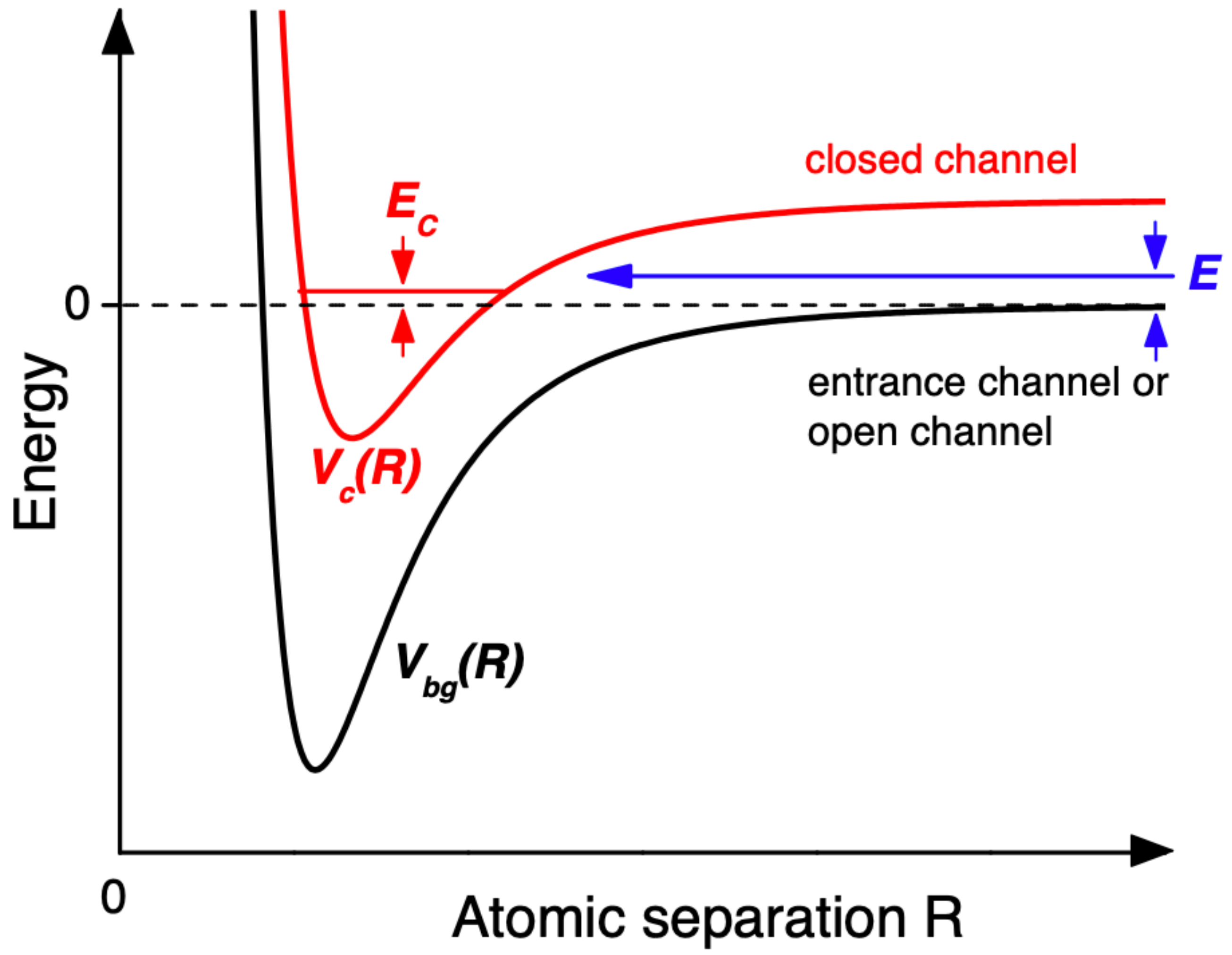
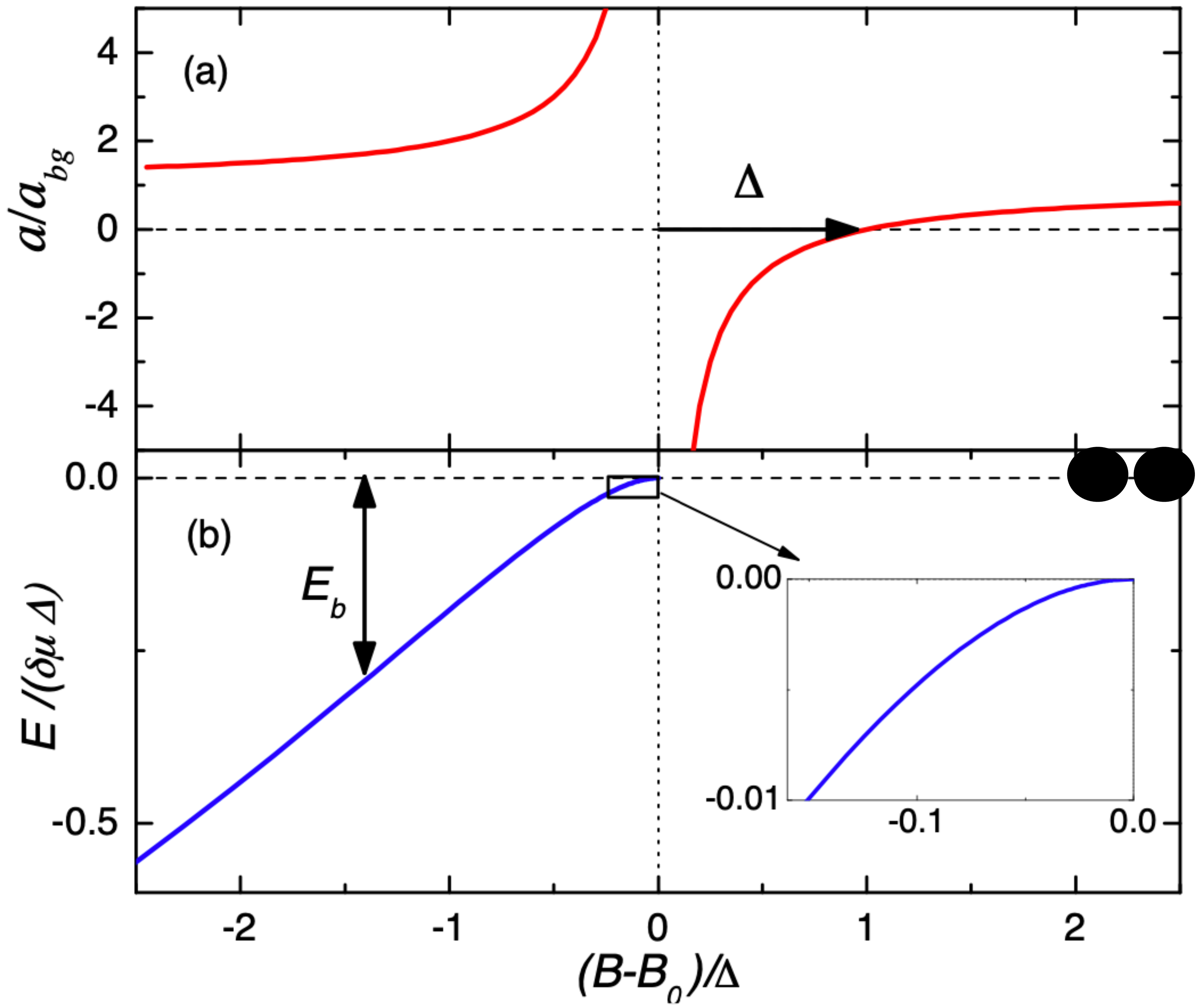
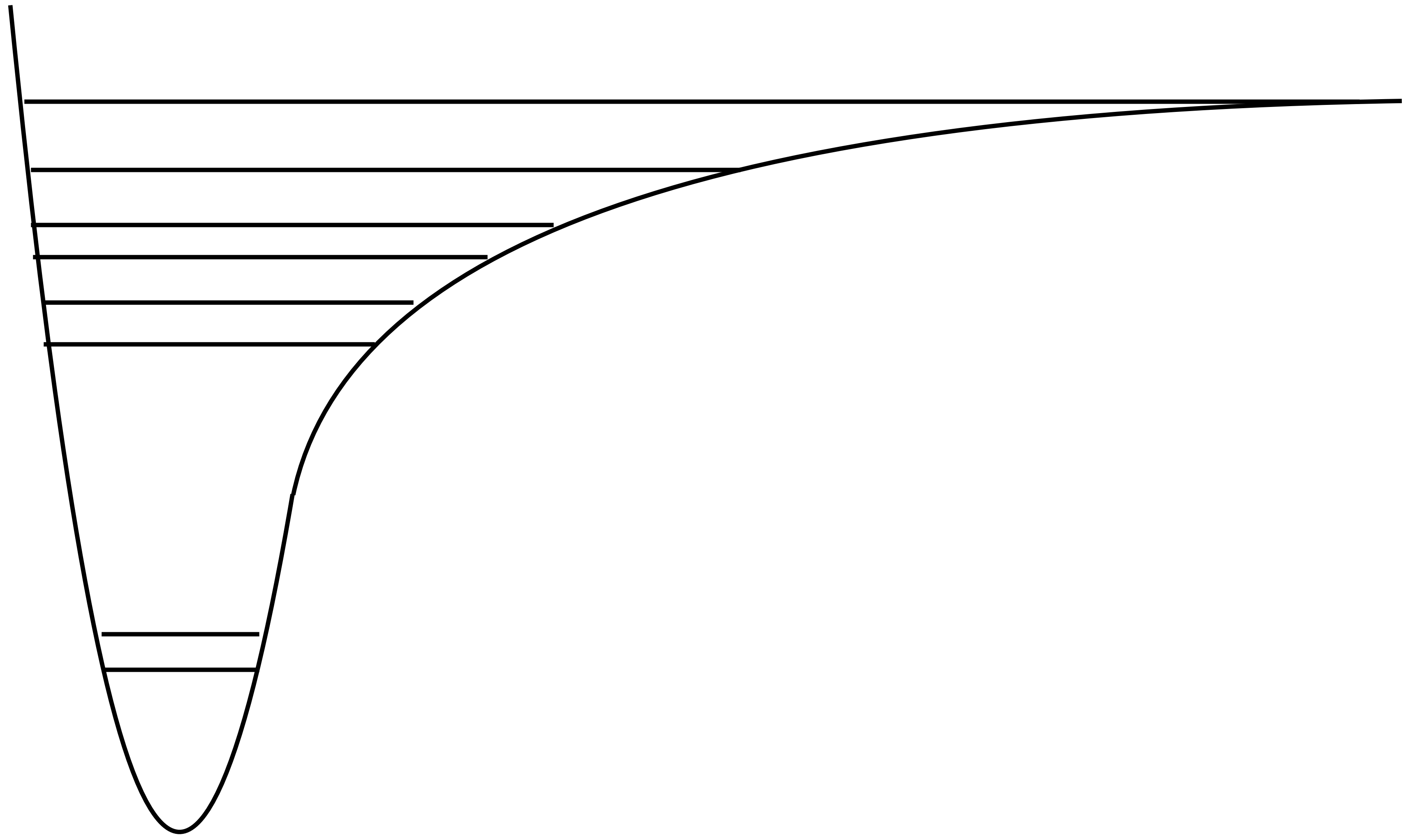
Weakly bound Feshbach molecules









- good for understanding long range collisions, temperature effects, BEC-BCS…

Weakly bound Feshbach molecules

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1+1

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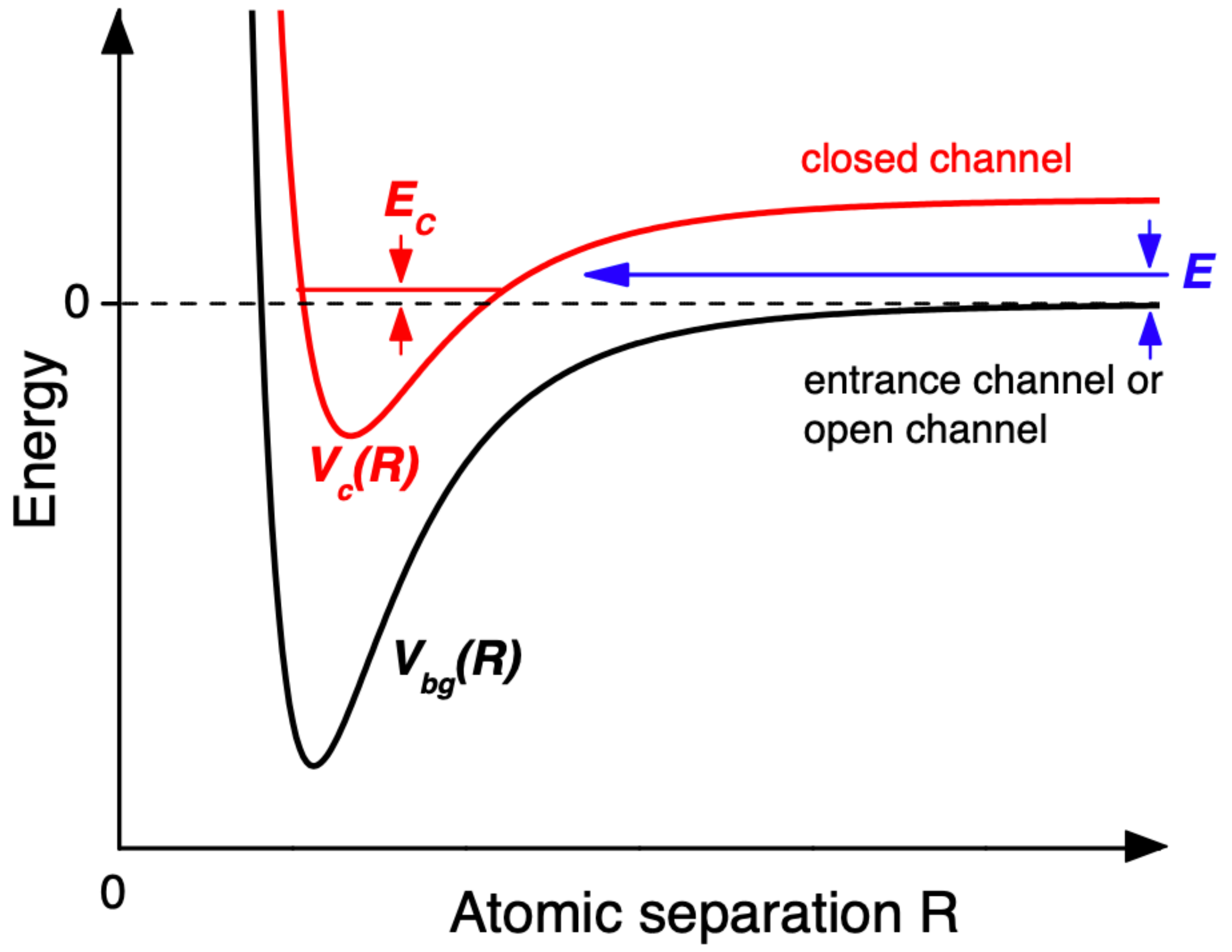

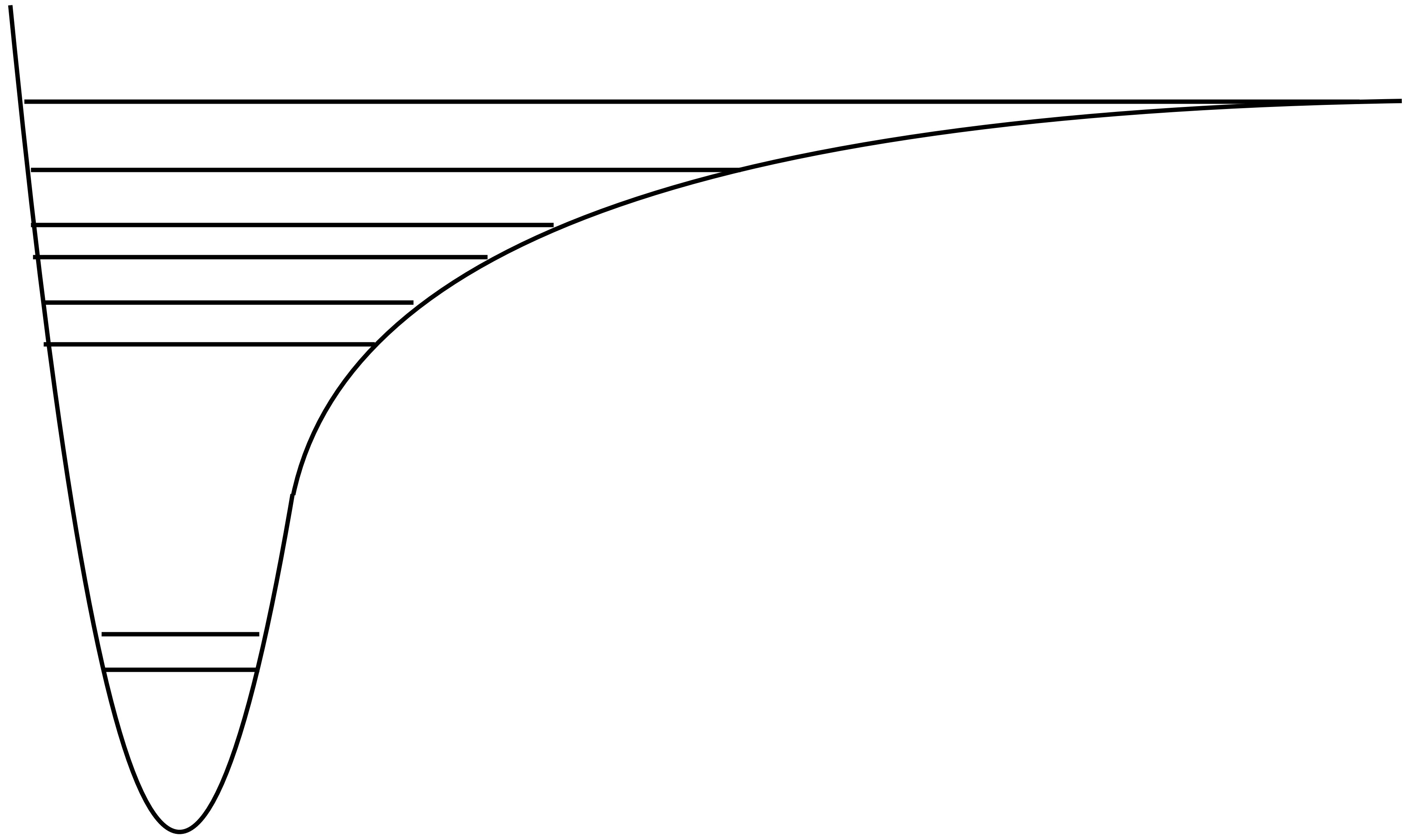

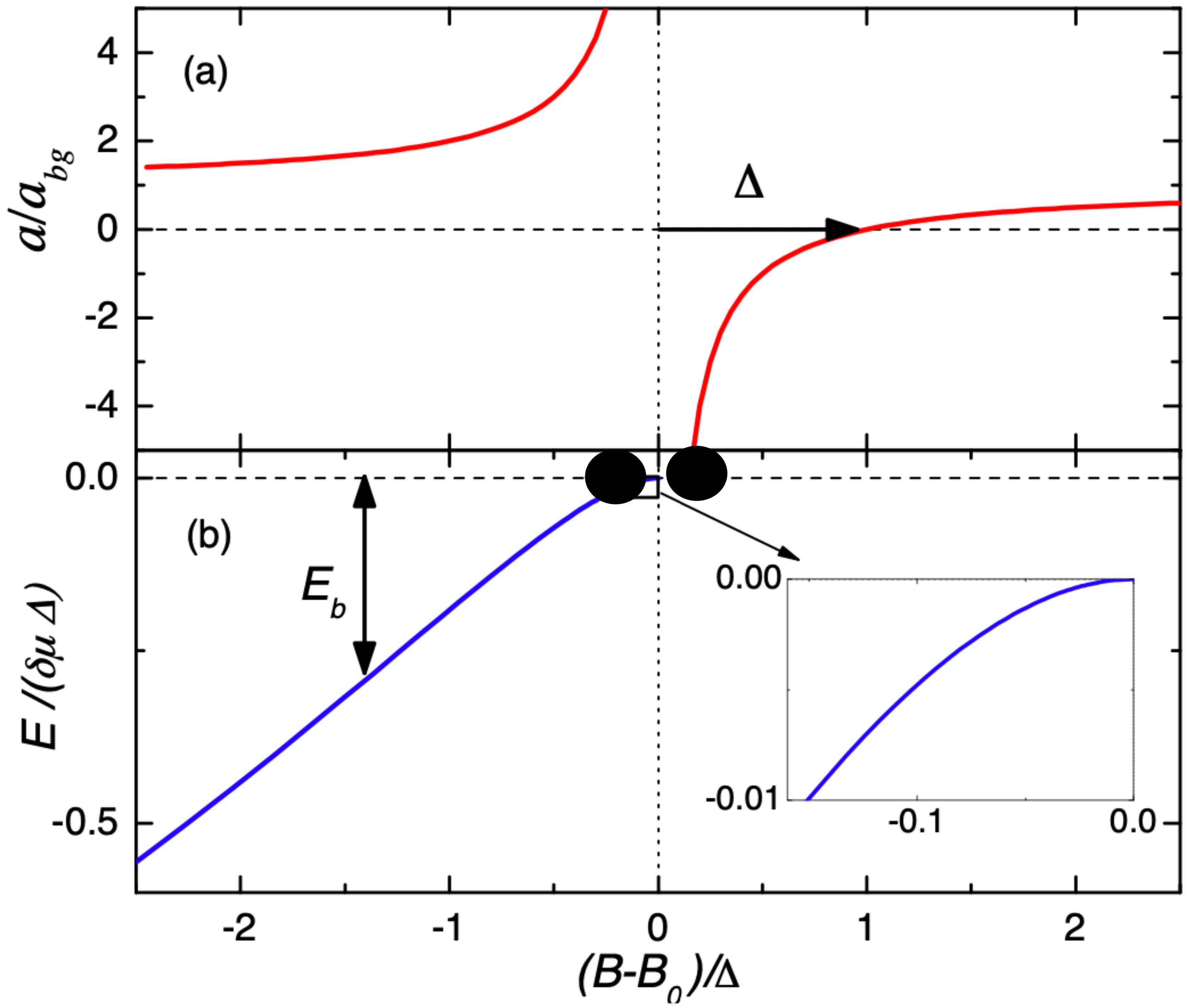

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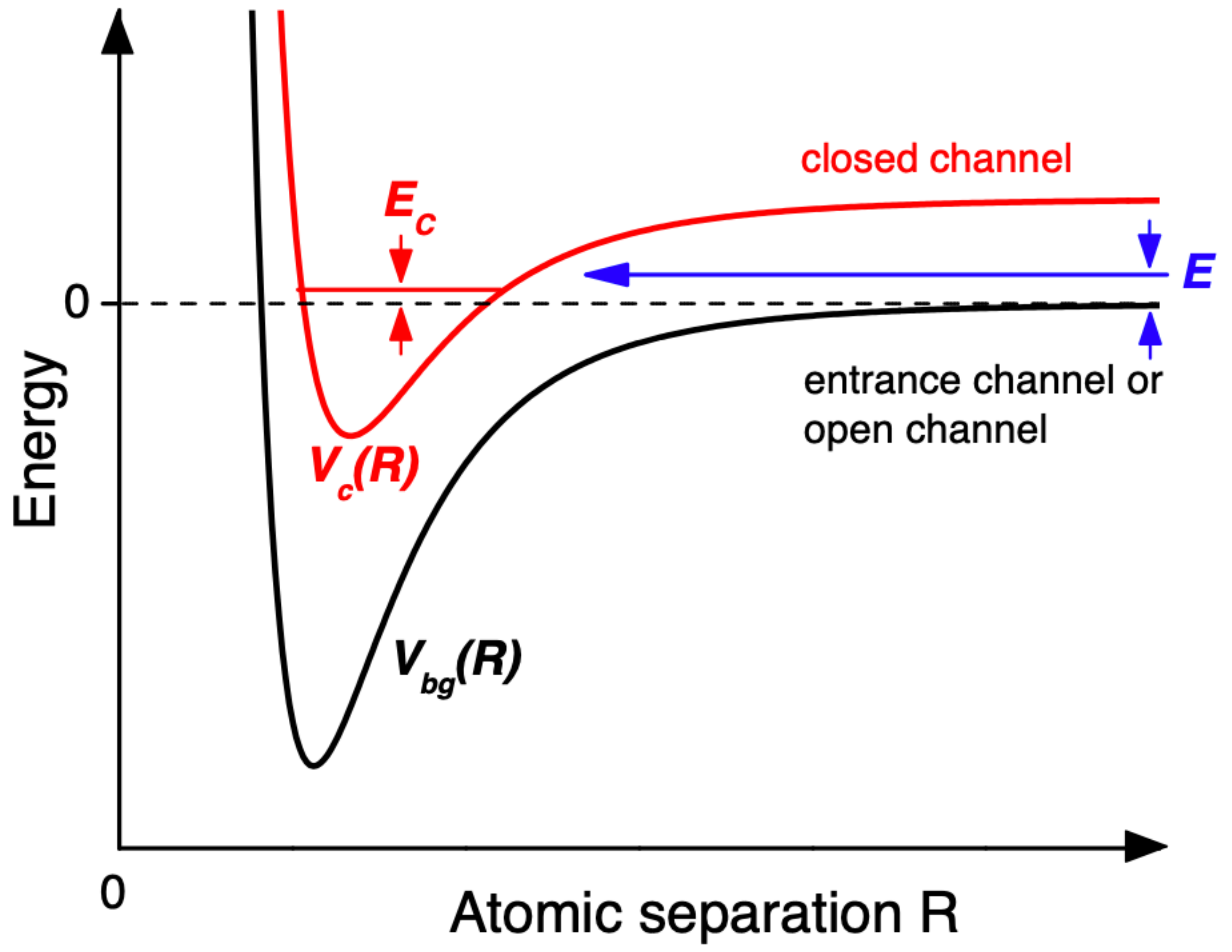

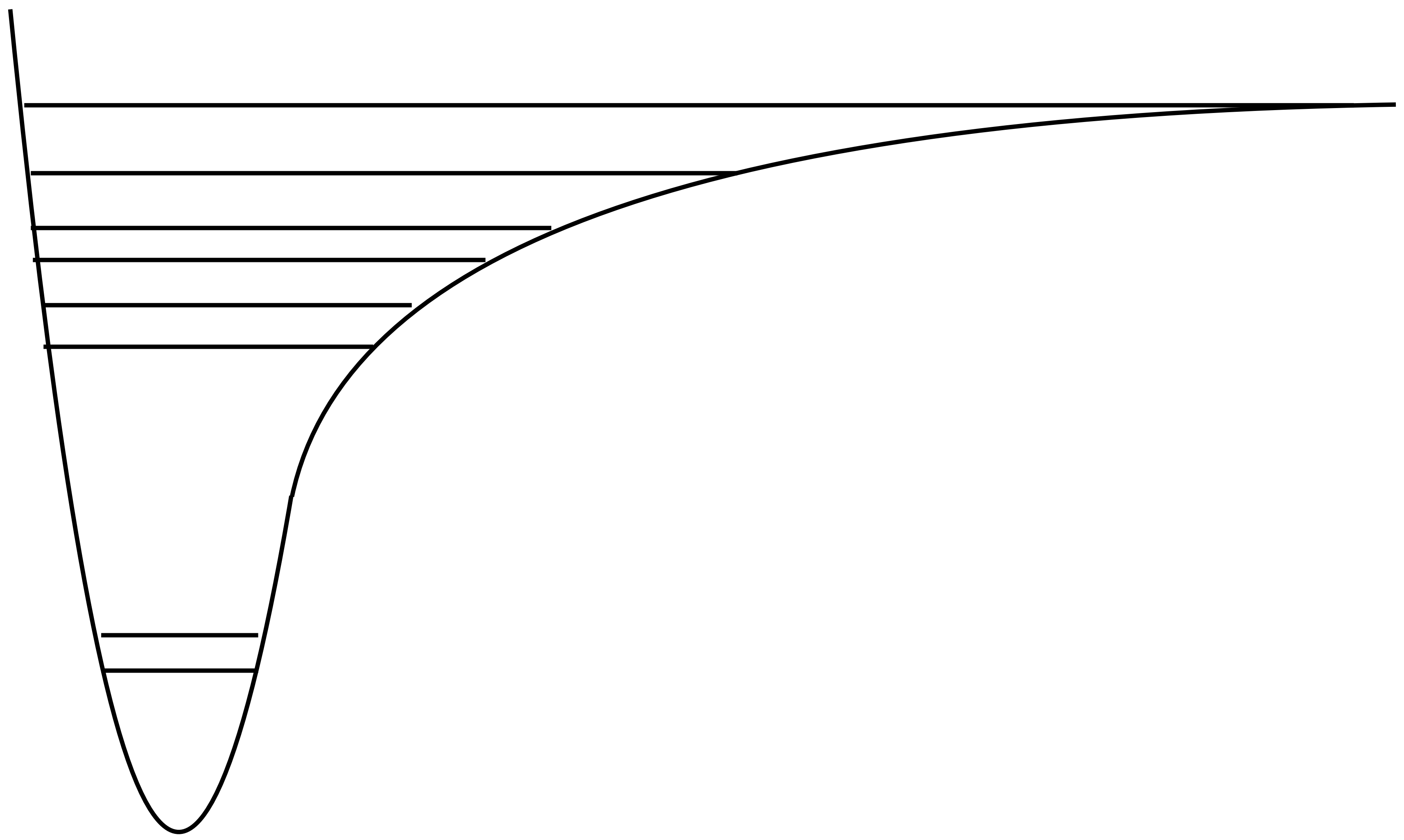

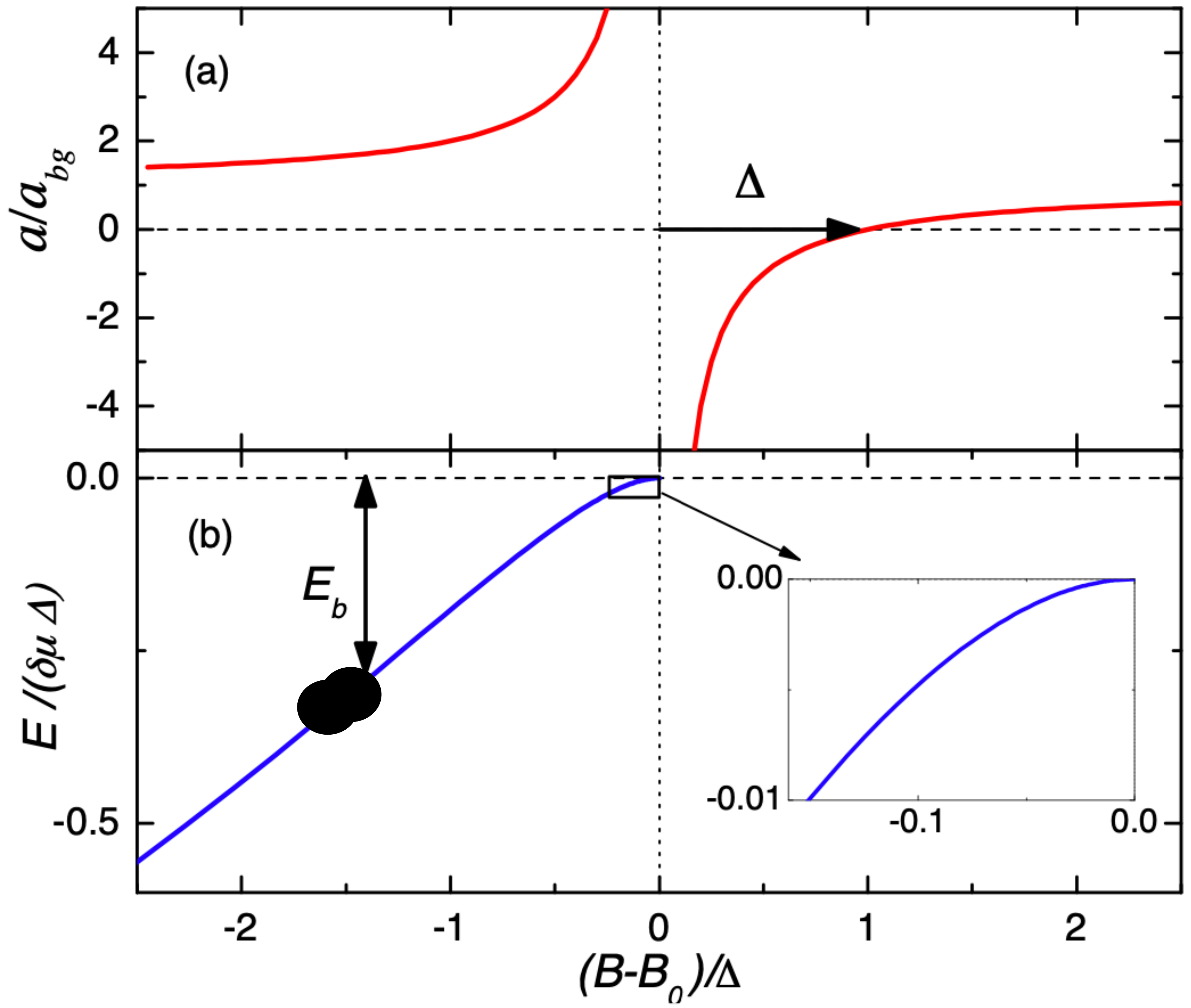

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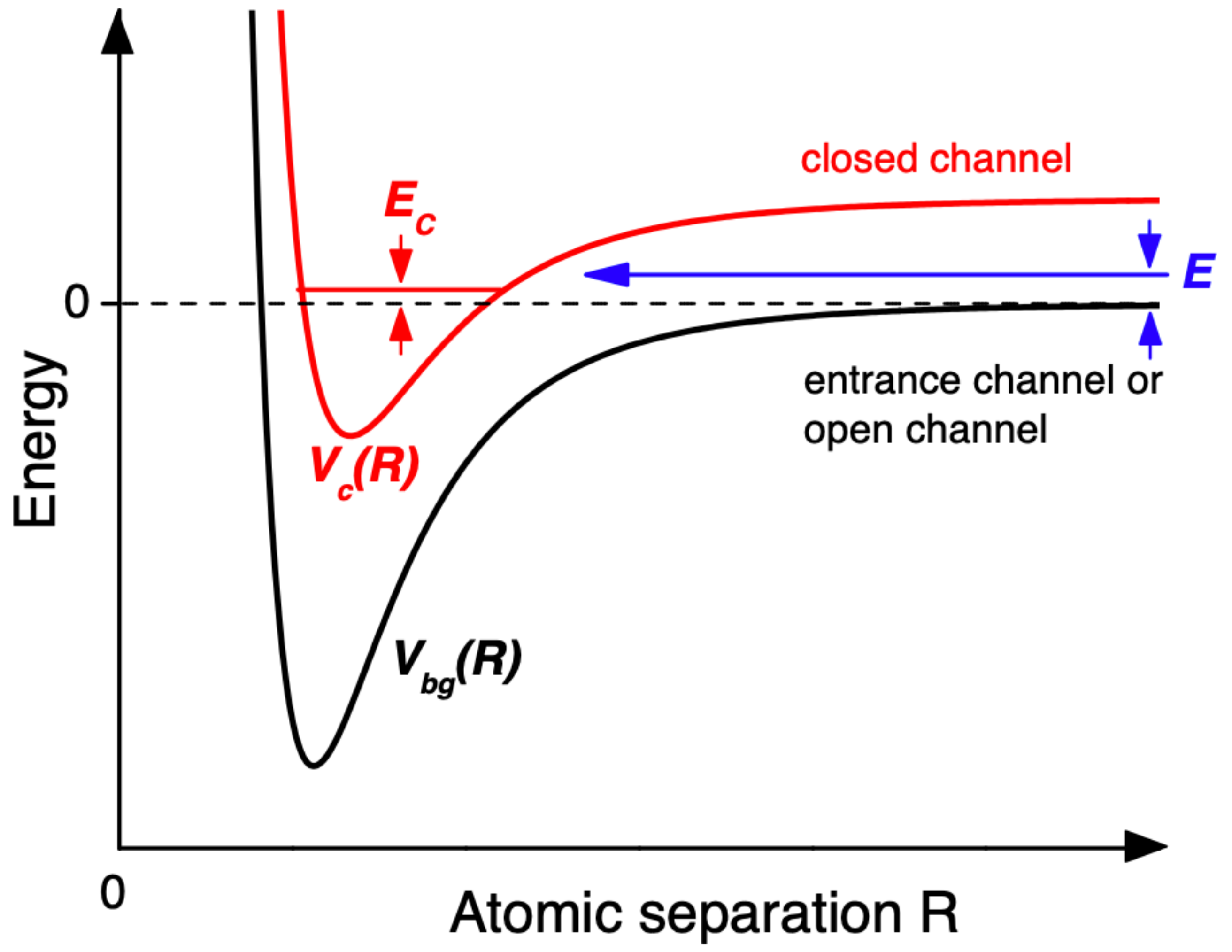

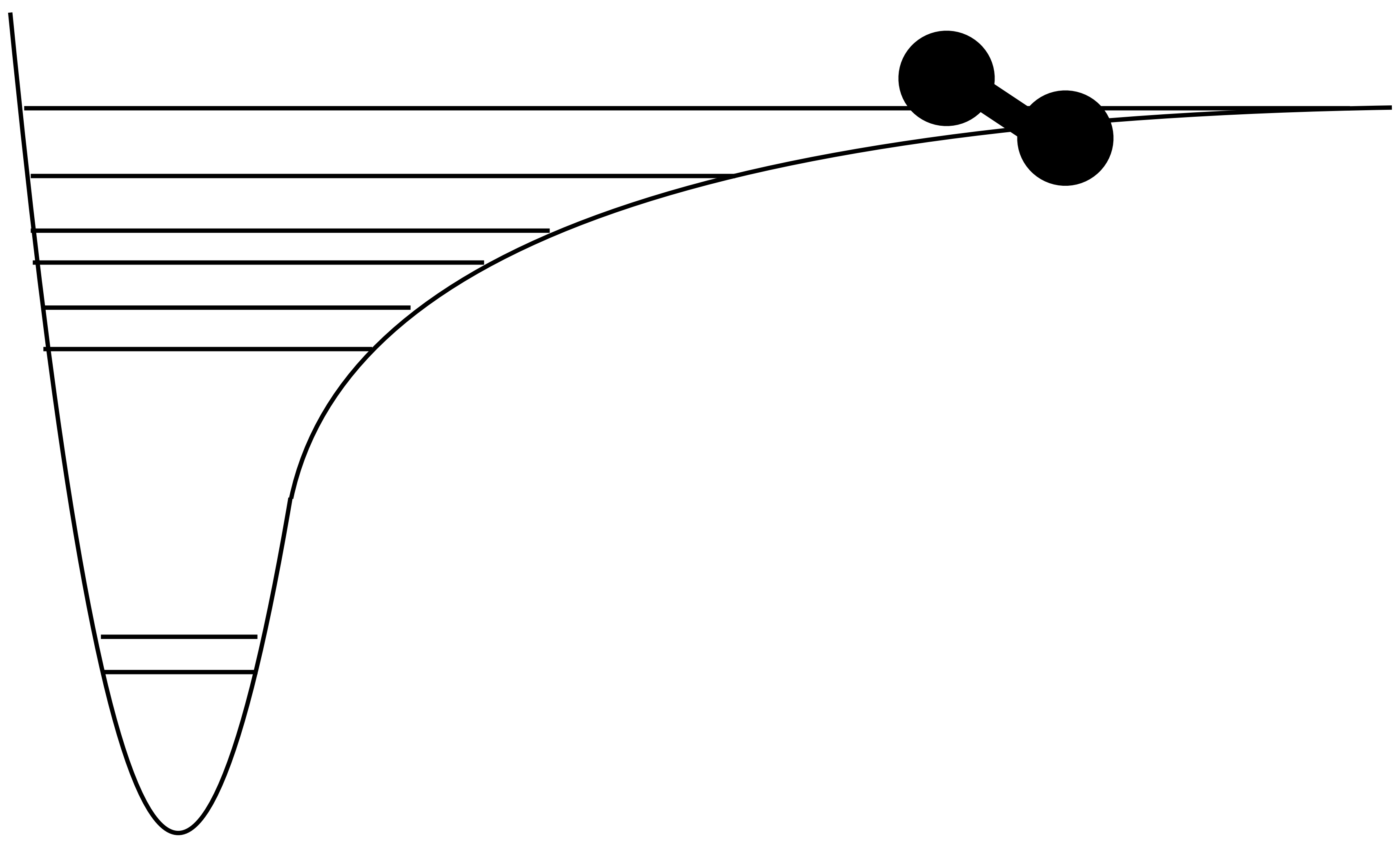

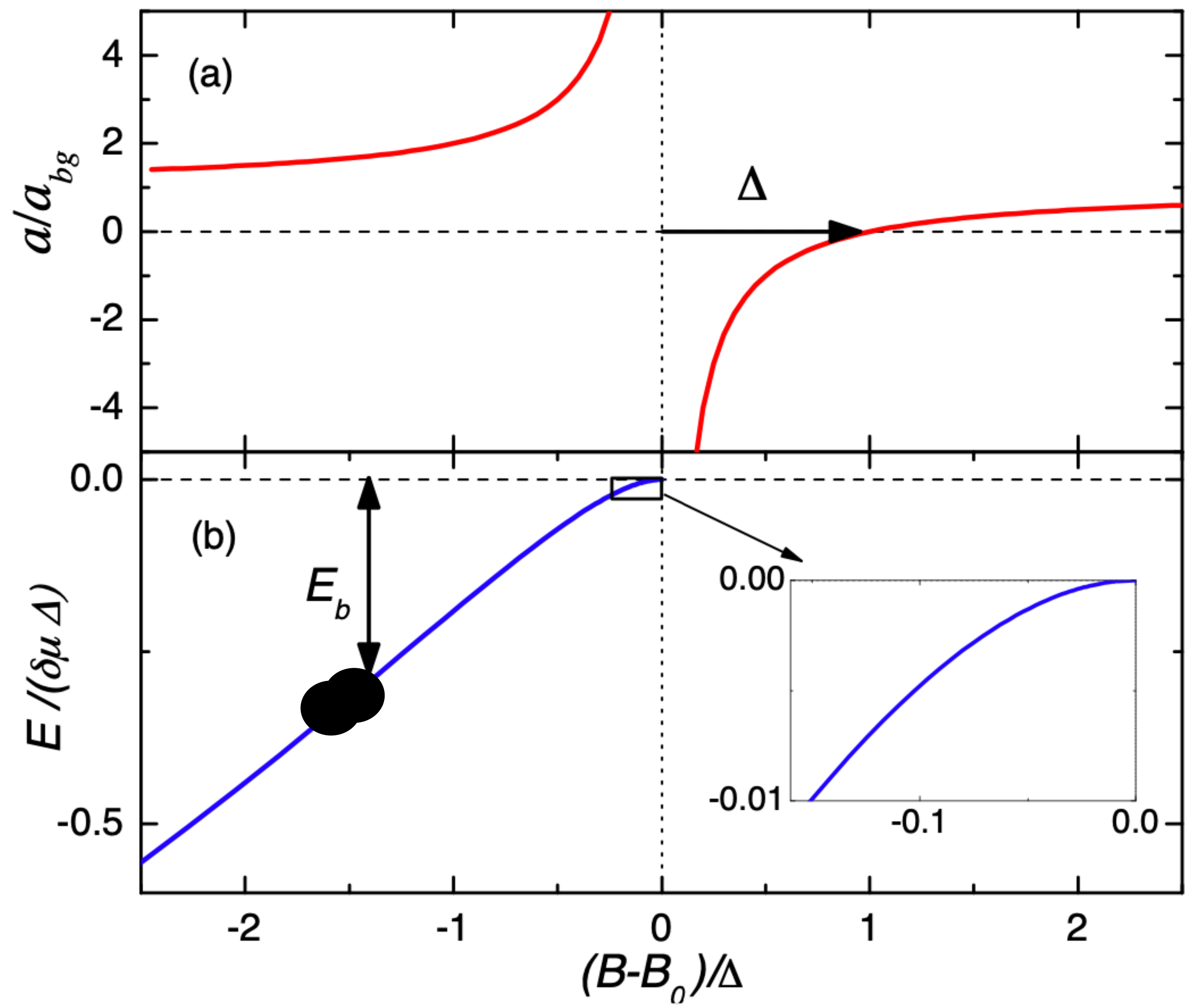

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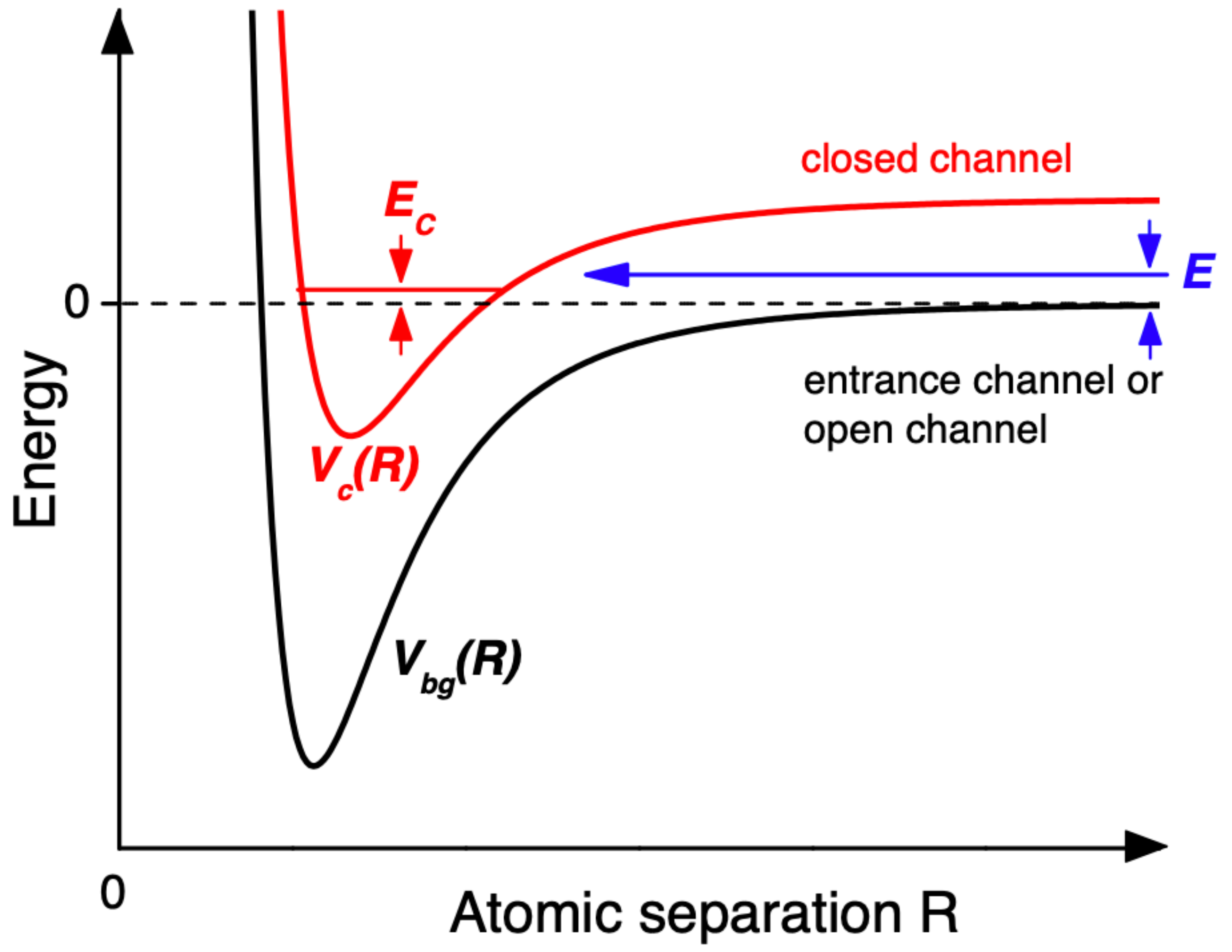

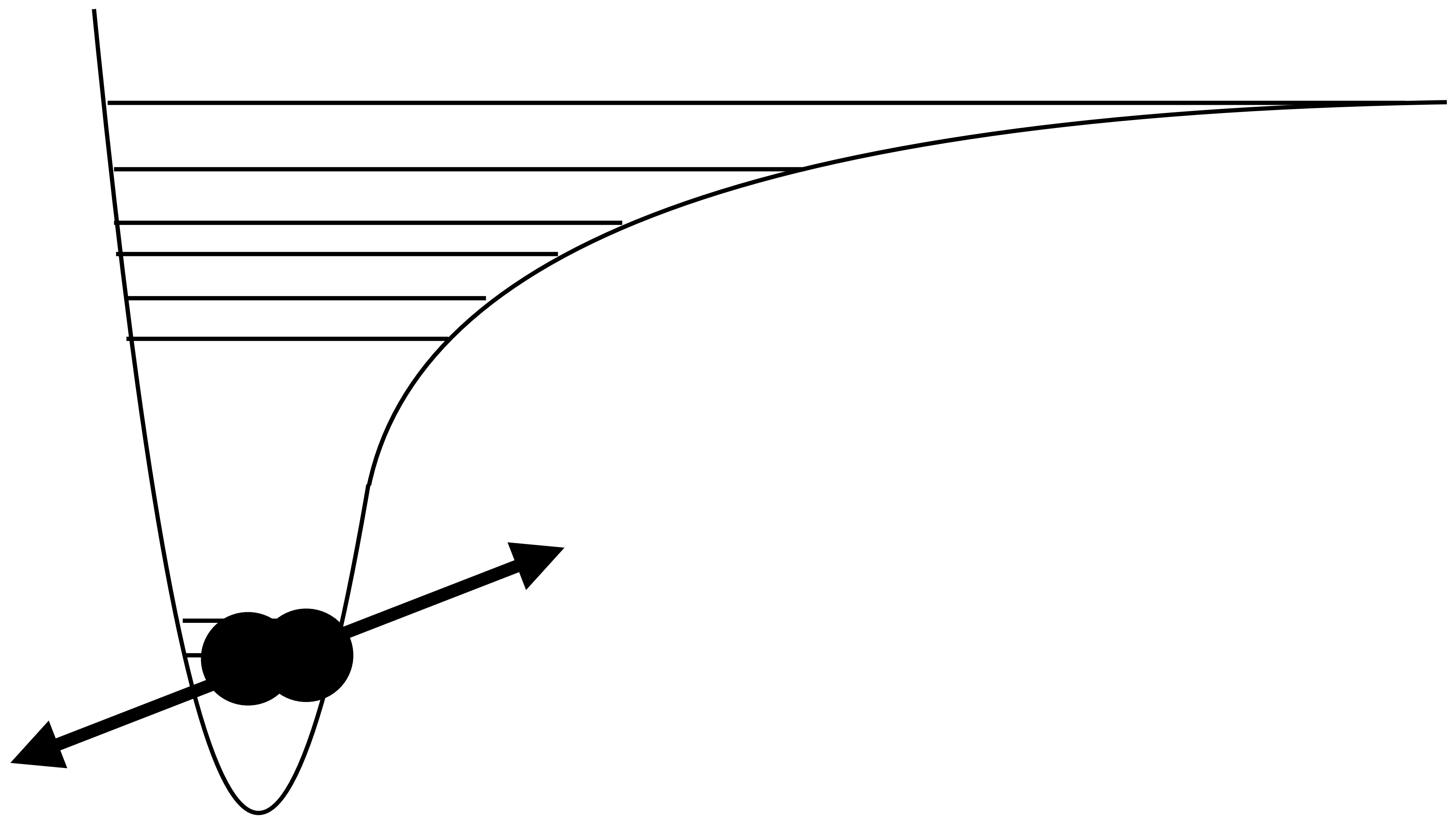

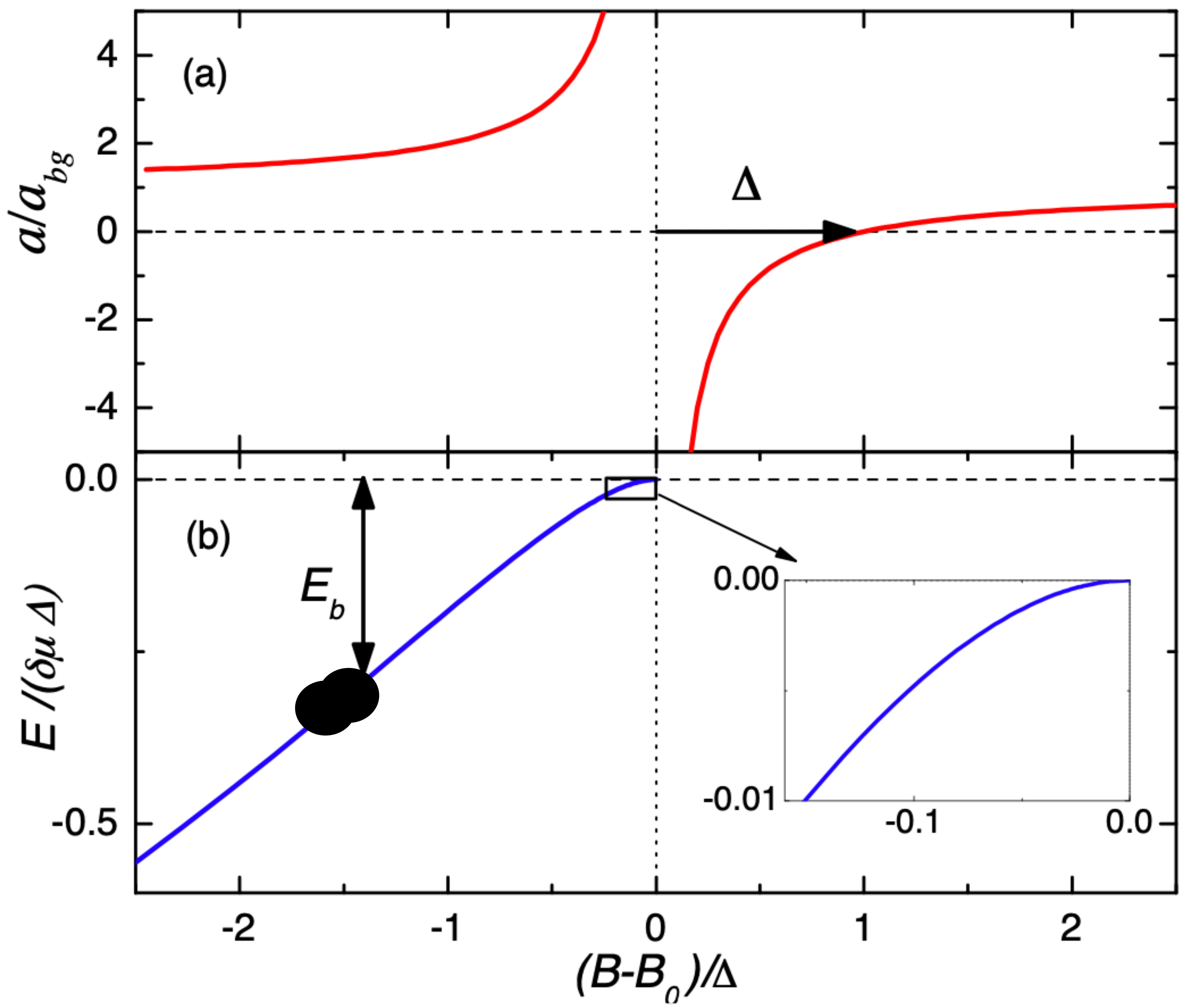

- good for understanding long range collisions, temperature effects, BEC-BCS…

Why to go to the ground state?

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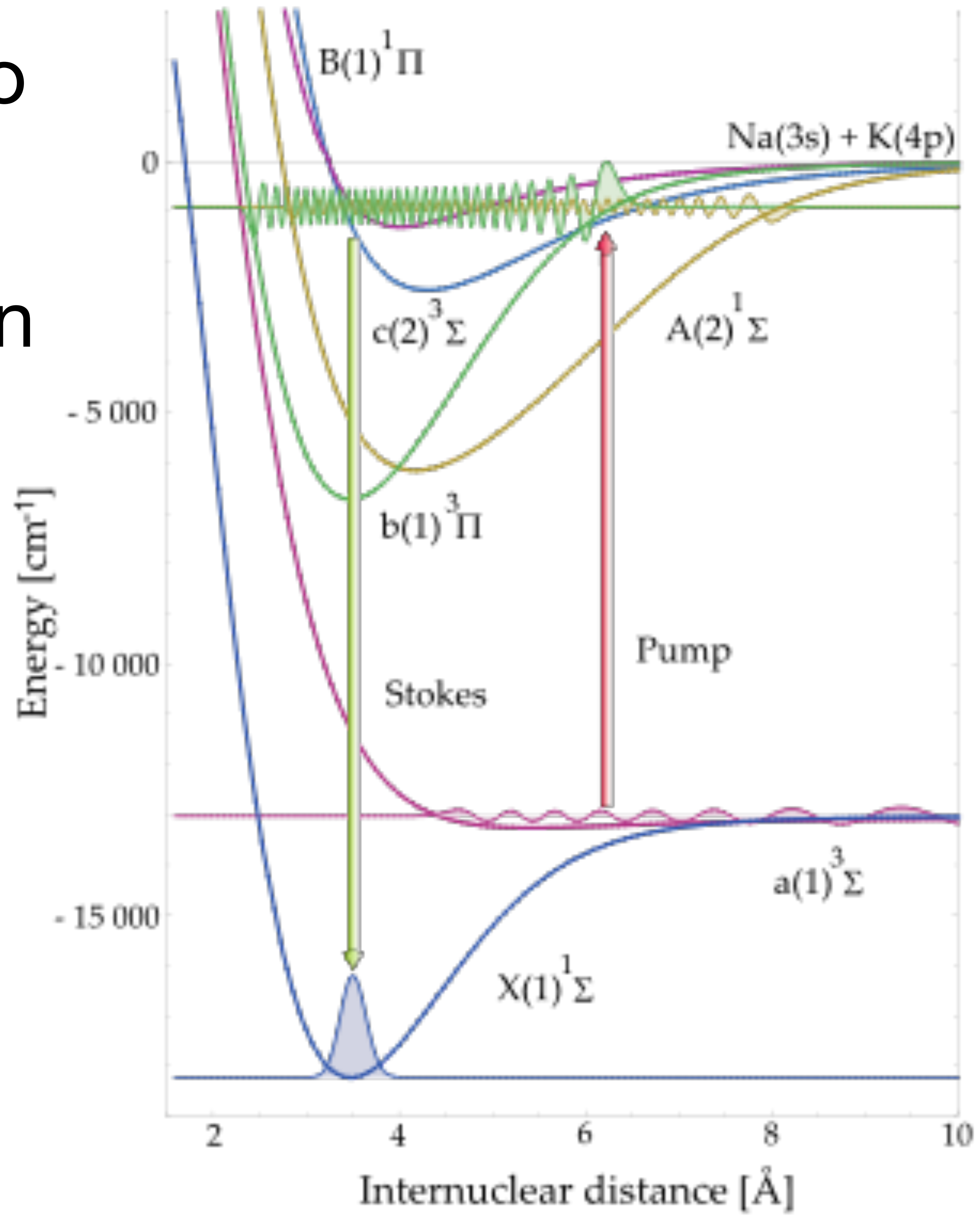
...

- Stability of ground state molecules: We want to reach **quantum degeneracy** as for atoms

- Very large dipole moment coming from electron charge distribution:
Long range dipole interactions

- Transfer from the weakly bound state to the ground state.

  - Challenges: - From very large to very small
    - Stay cold
    - THz Jump
      (no light, no MW, no RF)
    - Preserve quantum numbers
    - Choice not chemically reacting molecules



STIRAP

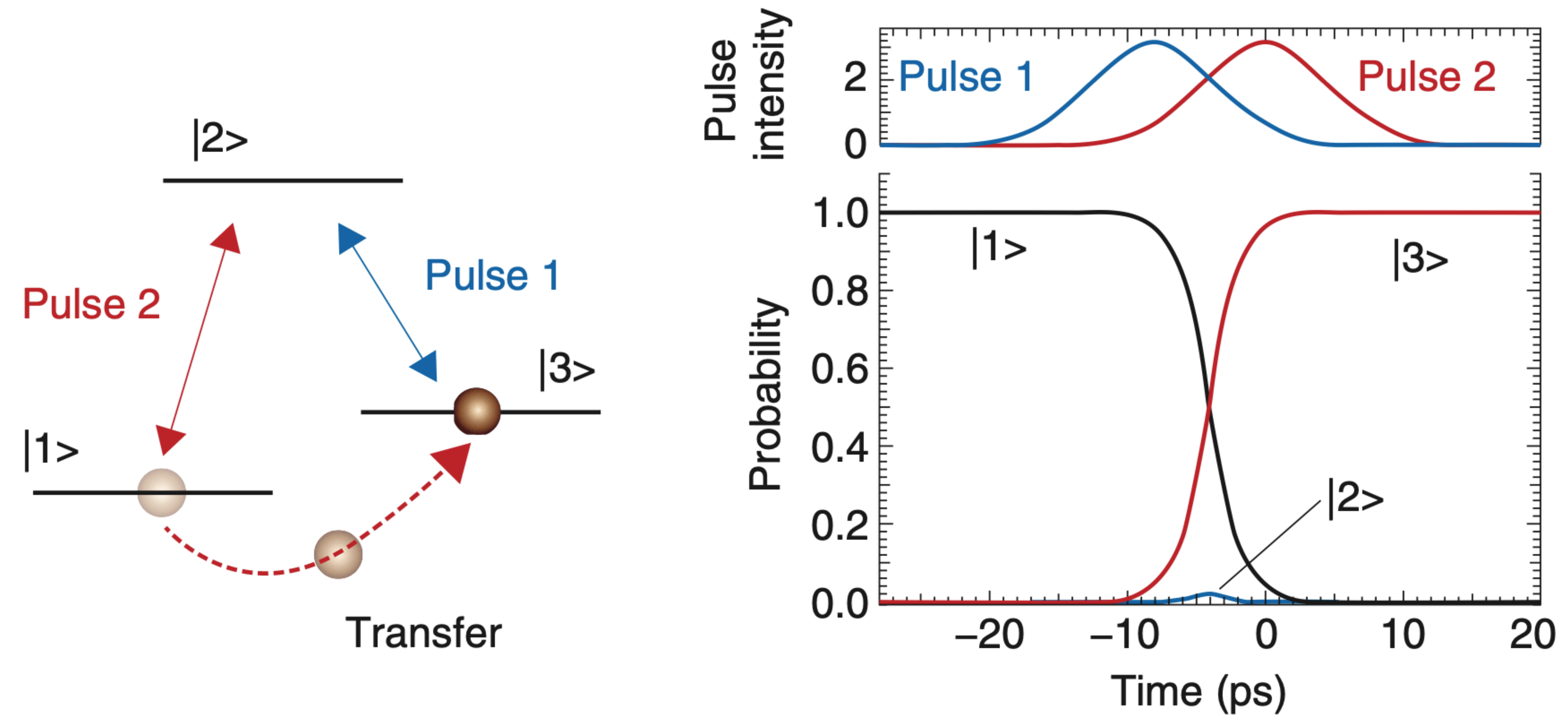
- STImulated Rapid Adiabatic Passage

Coherent transfer from one state to a another.

Anti-intuitive sequence of pulses (to adiabatically rotate a dark state to the target one)

Bergmann:

“It’s like when you have to take a bus to go to the airport, but the fastest way to reach the final destination is that the plane has to leave before you take the bus”



Stimulated Raman adiabatic passage in physics, chemistry, and beyond

Nikolay V. Vitanov, Andon A. Rangelov, Bruce W. Shore, and Klaas Bergmann
Rev. Mod. Phys. **89**, 015006 – Published 8 March 2017

STIRAP

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1+1

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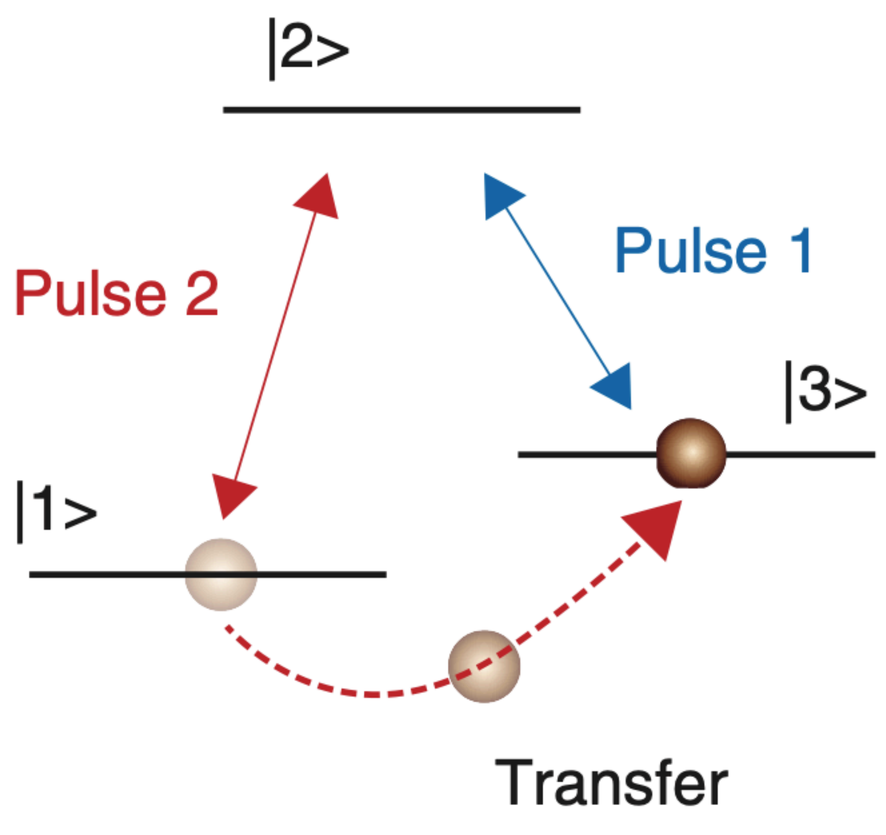

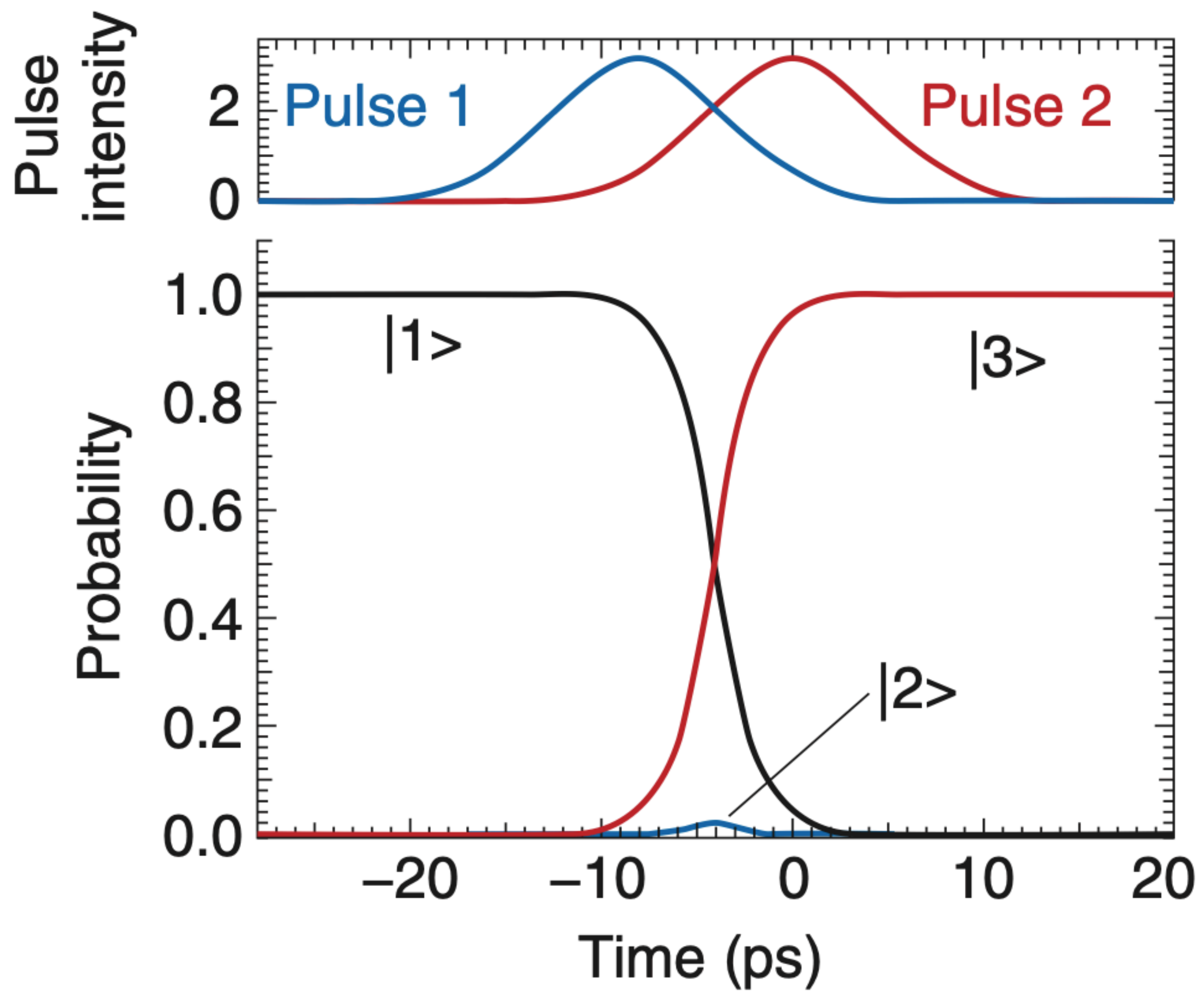

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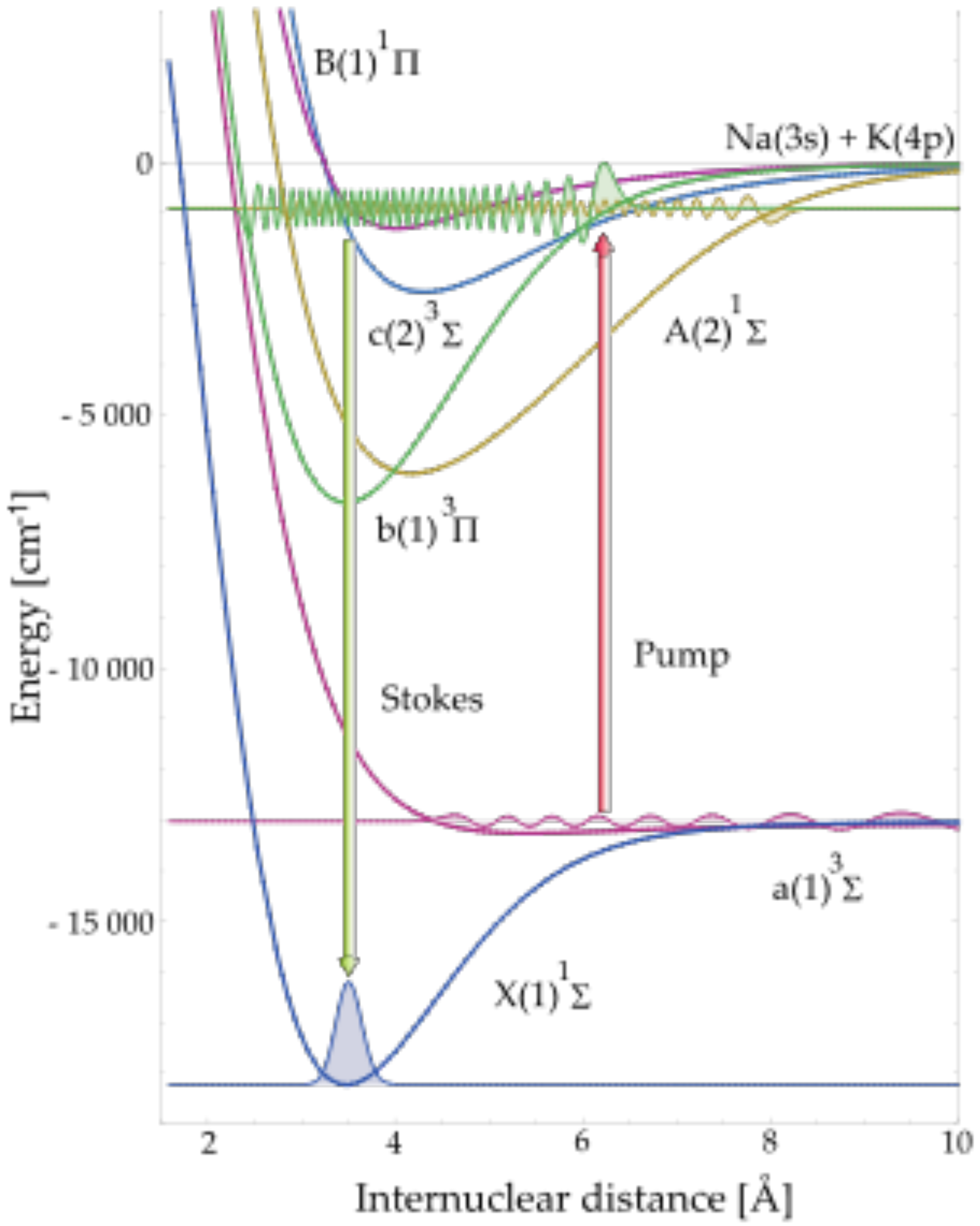
STIRAP

- Two (or more) very stable laser (to remain in the dark state)
- Good spatial overlap between initial and intermediate and final state
- Good mixing of quantum numbers



Implemented with 4 photons (Cs in IBK)

and in many other atomic systems…

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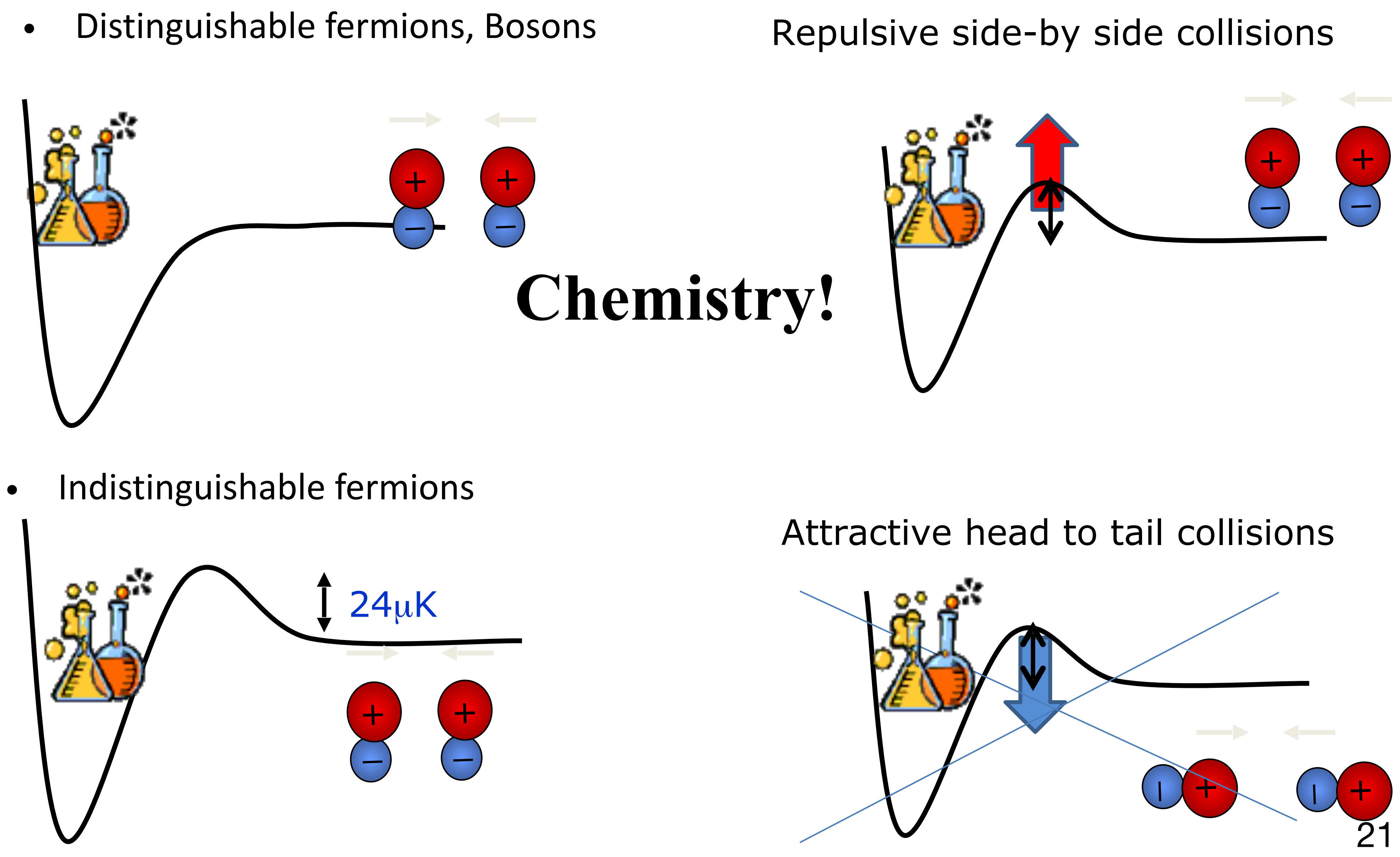
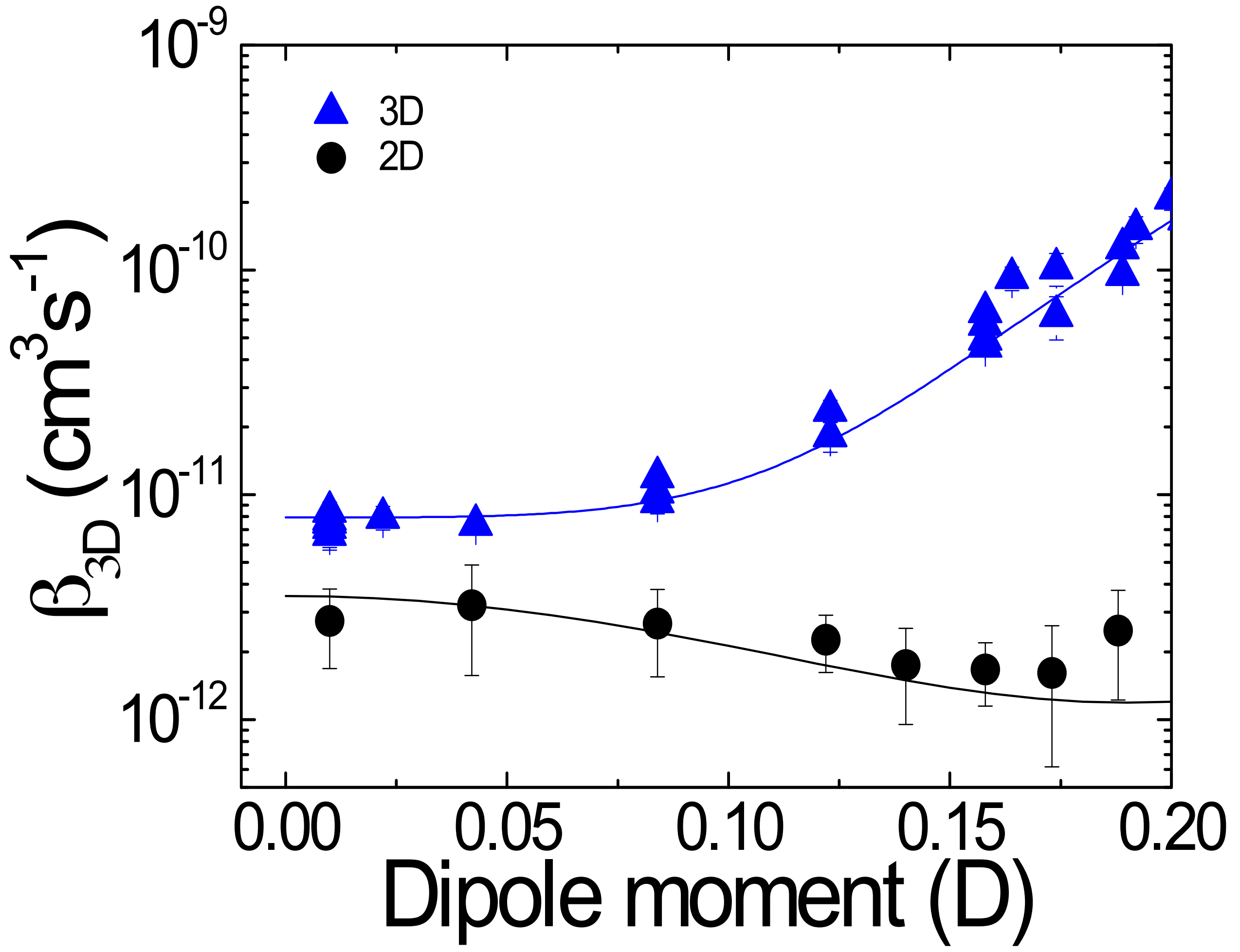
Experiments with molecules

- Changing chemical reaction speed with an E and B field





- Study of chemical reactions

Experiments with molecules

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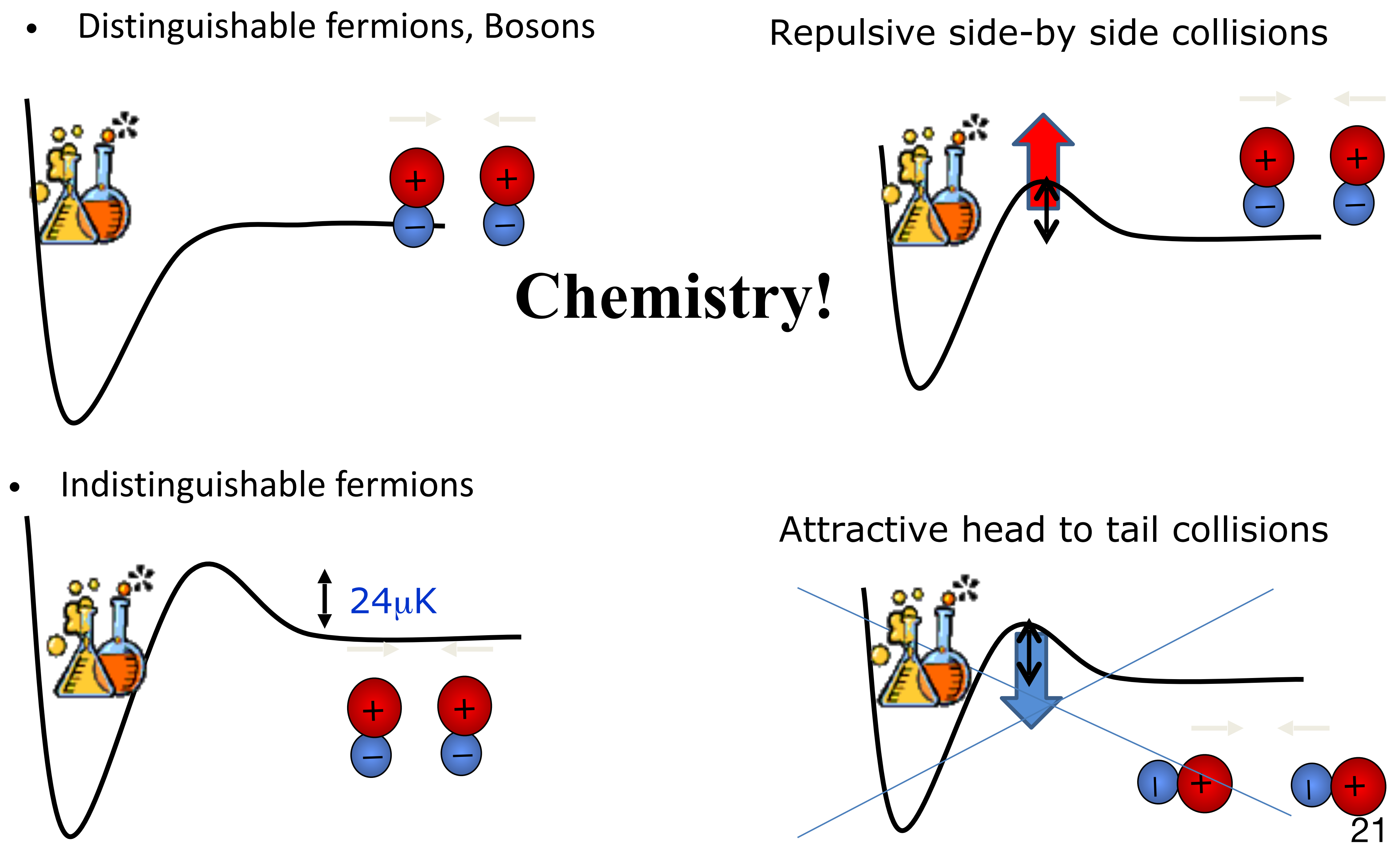

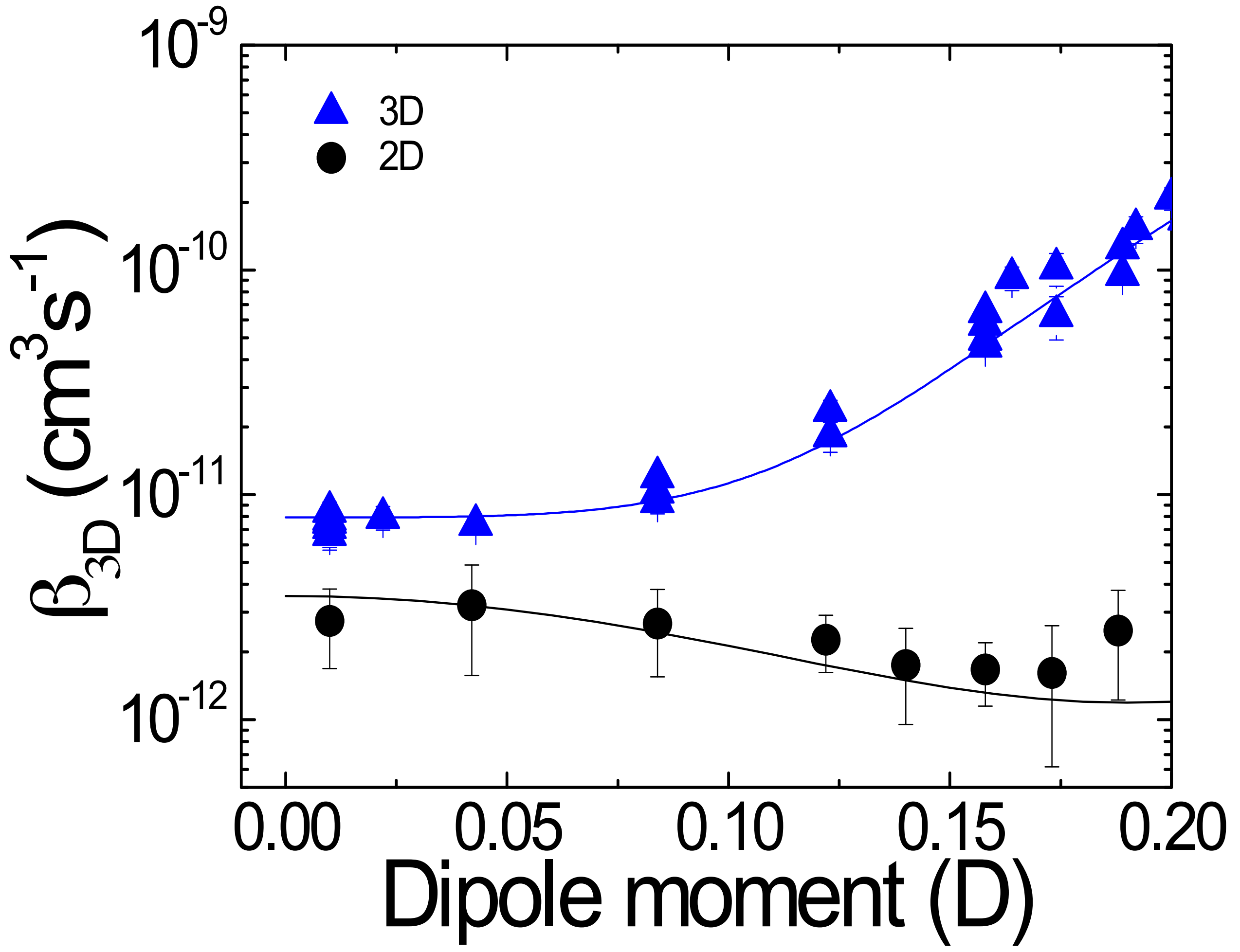

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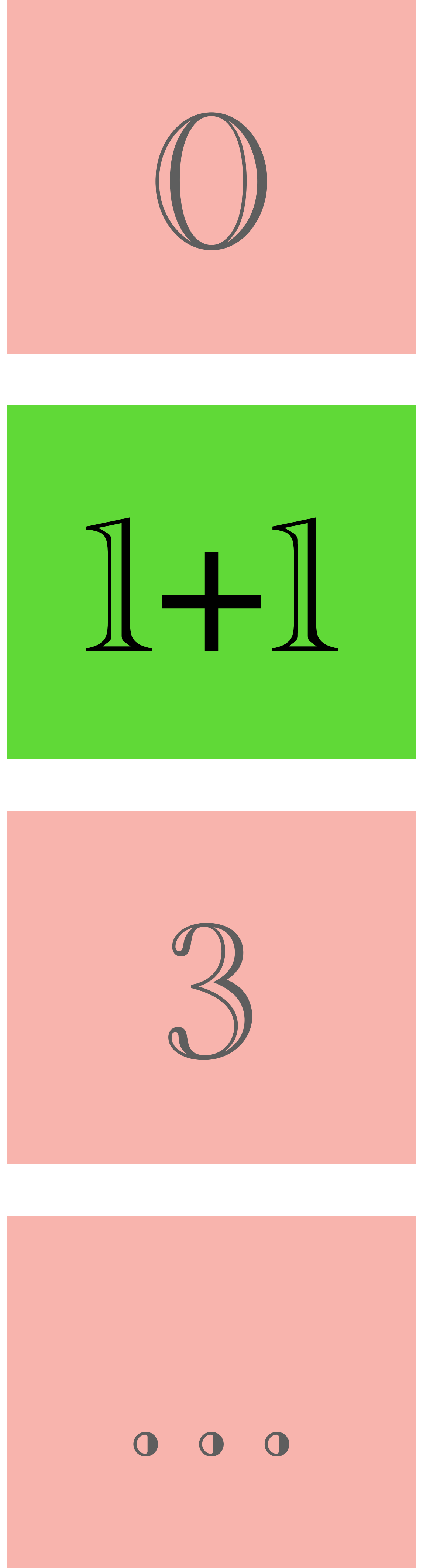

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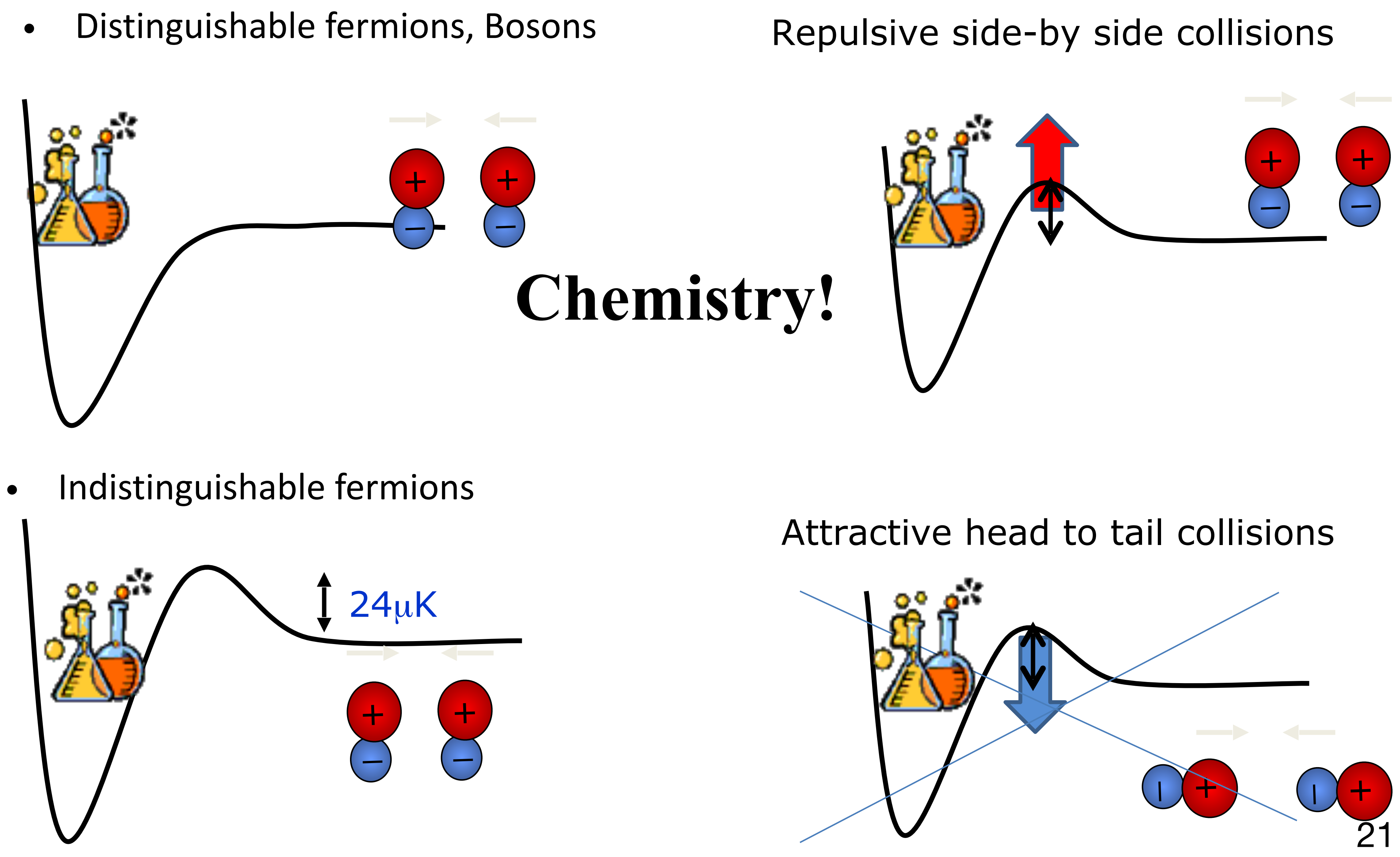

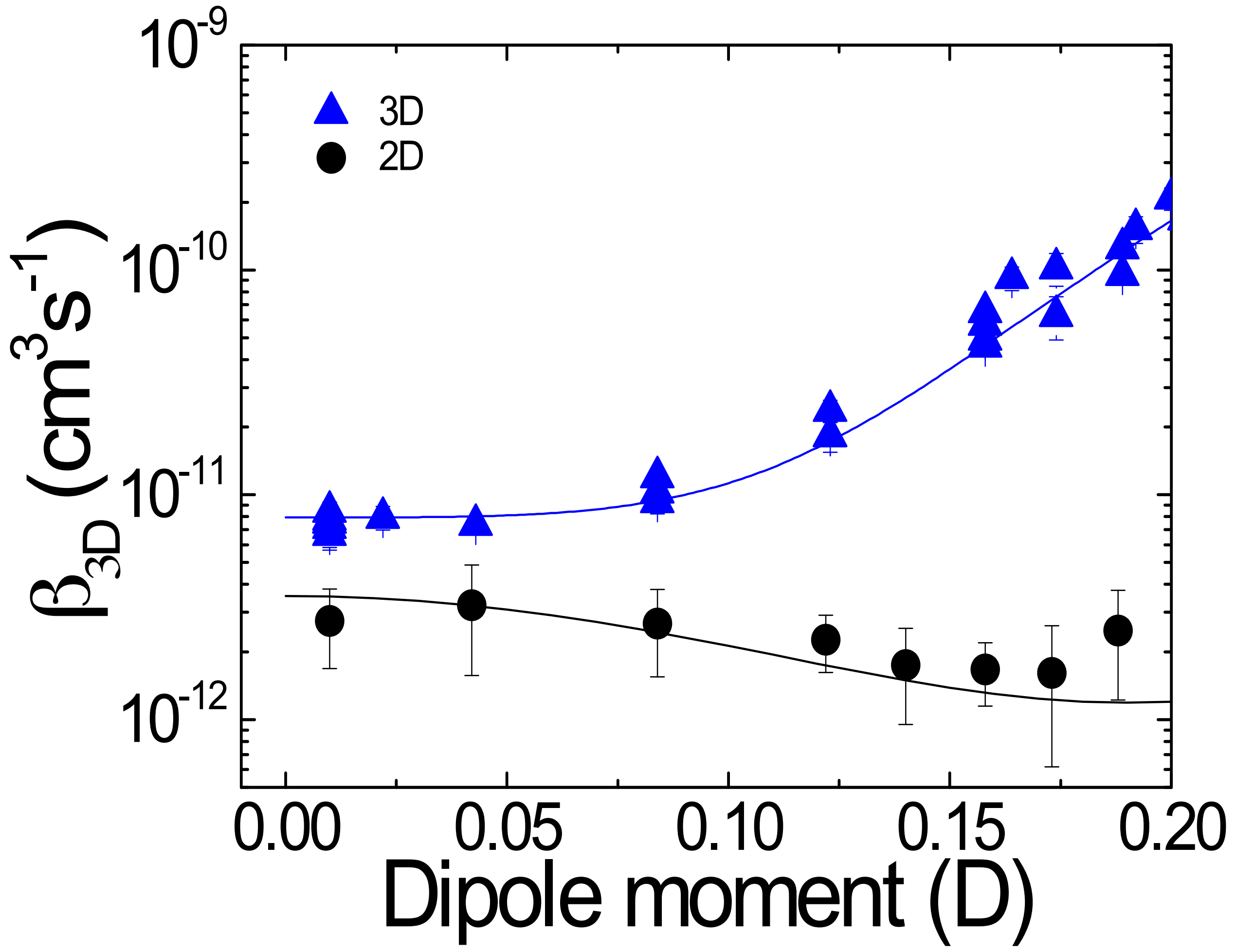

- Study of chemical reactions
- Recently evidences of degenerate fermi gases of KRb (Jila) and NaK (Munich)
- Recent development: Molecules in tweezers for quantum computation, analysis of losses with mass spectrometer…

Tuning knobs for molecules

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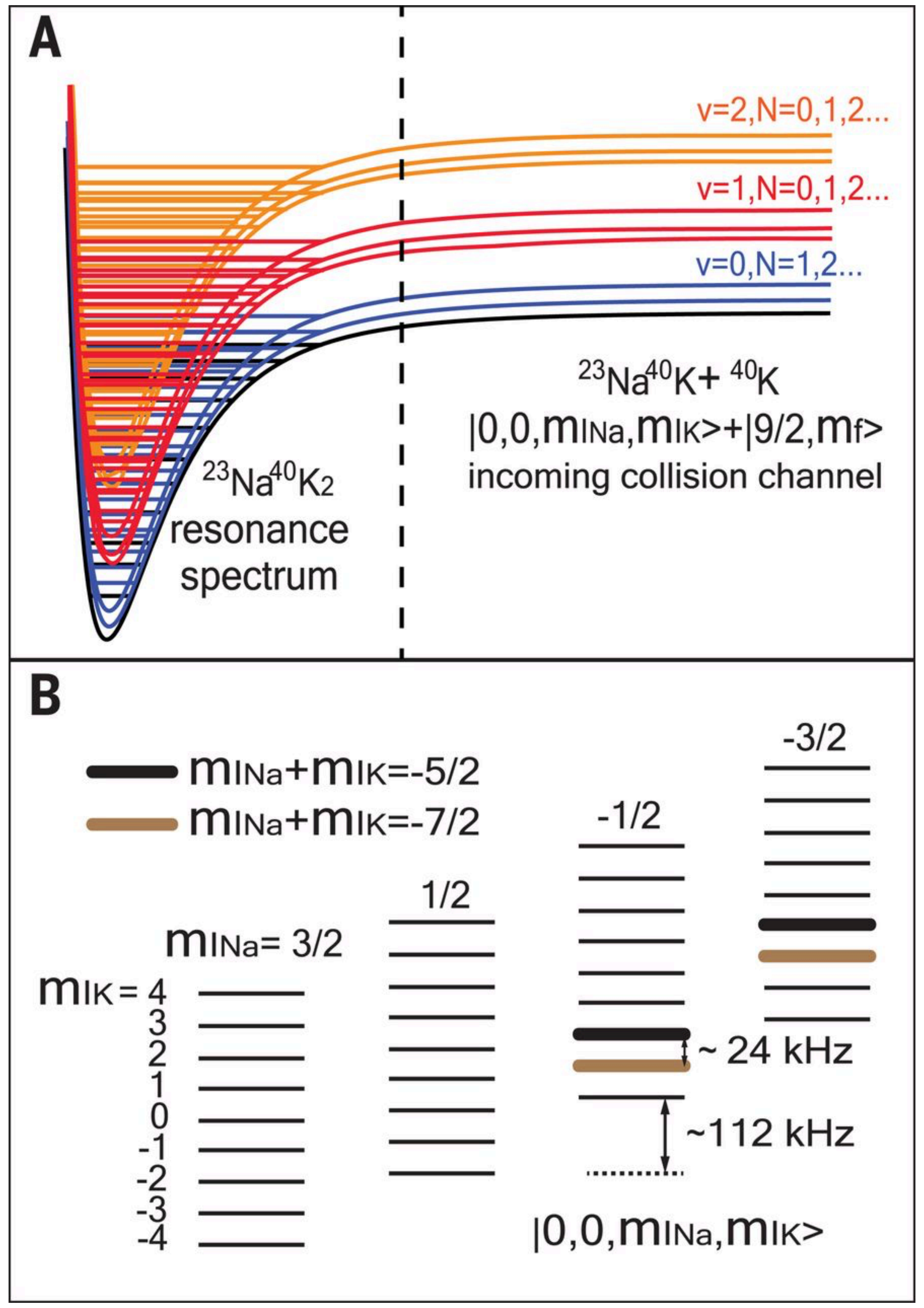
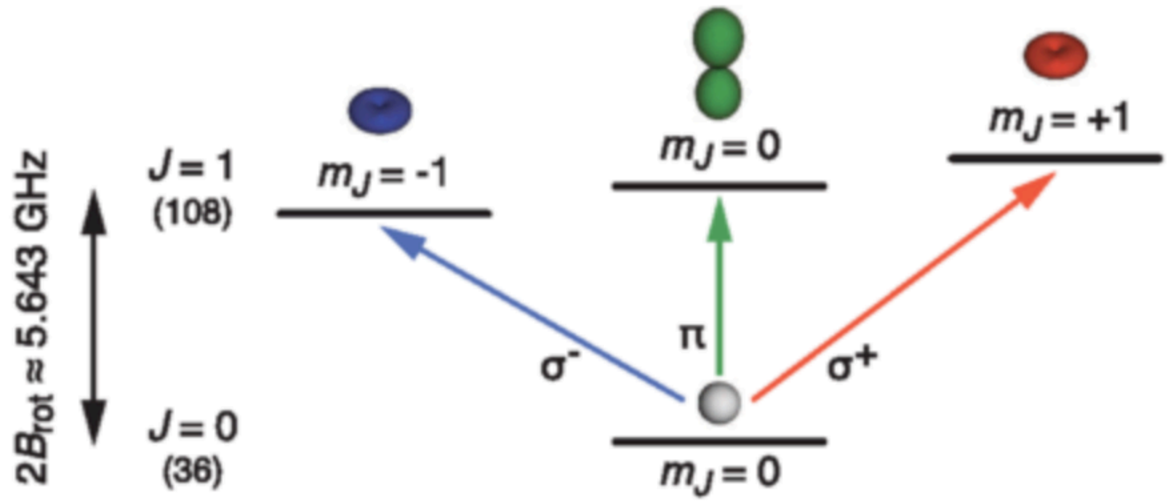
Observation of magnetically tunable Feshbach resonances in ultracold $^{23}Na^{40}K$ + ^{40}K collisions

HUAN YANG, DE-CHAO ZHANG, LAN LIU, YA-XIONG LIU, JUE NAN, BO ZHAO, AND JIAN-WEI PAN Authors Info & Affiliations

SCIENCE • 18 Jan 2019 • Vol 363, Issue 6424 • pp. 261-264 • DOI: 10.1126/science.aau5322





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Sebastian A. Will, Jee Woo Park, Zoe Z. Yan, Huanqian Loh, and Martin W. Zwierlein
Phys. Rev. Lett. **116**, 225306 – Published 3 June 2016

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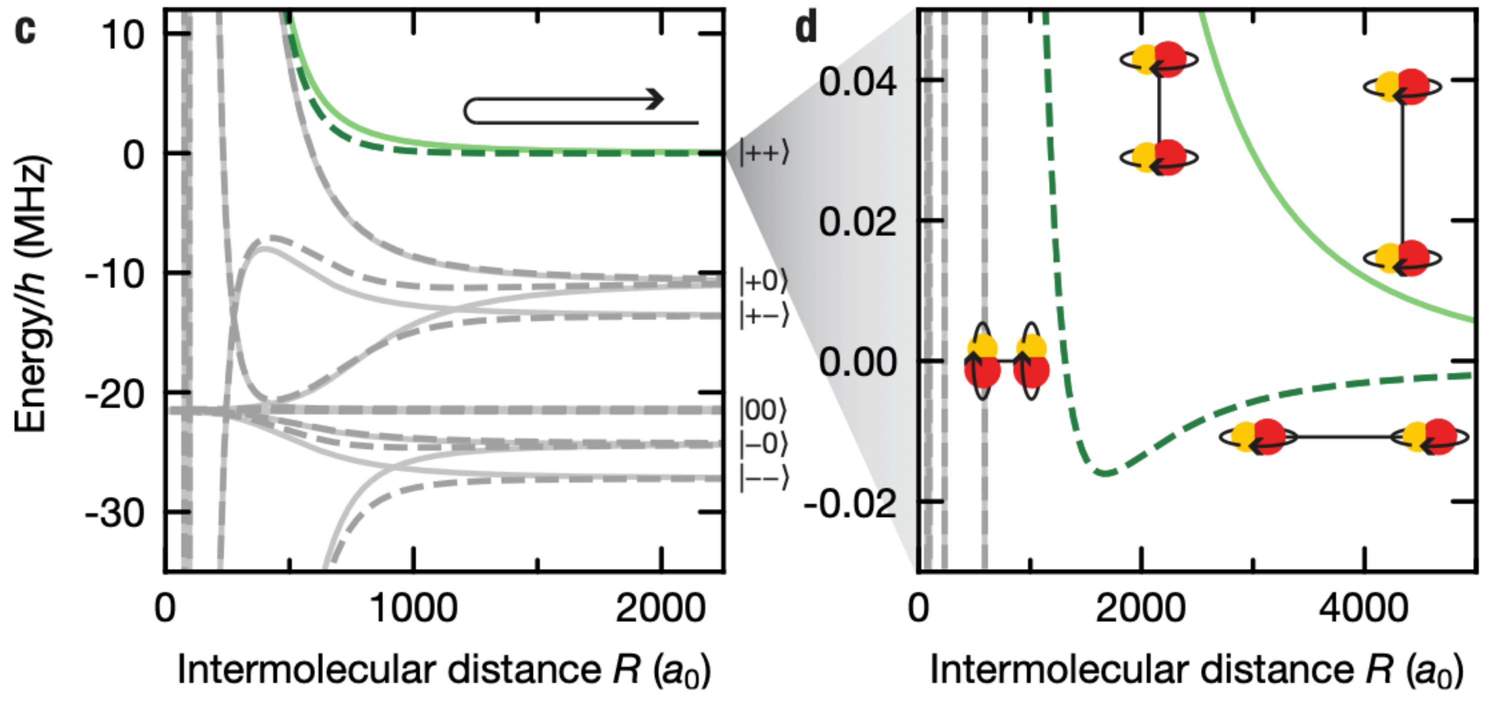

Evaporation of microwave-shielded polar molecules to quantum degeneracy

Andreas Schindewolf,[1,2] Roman Bause,[1,2] Xing-Yan Chen,[1,2] Marcel Duda,[1,2] Tijs Karman,[3] Immanuel Bloch,[1,2,4] and Xin-Yu Luo[1,2,*]

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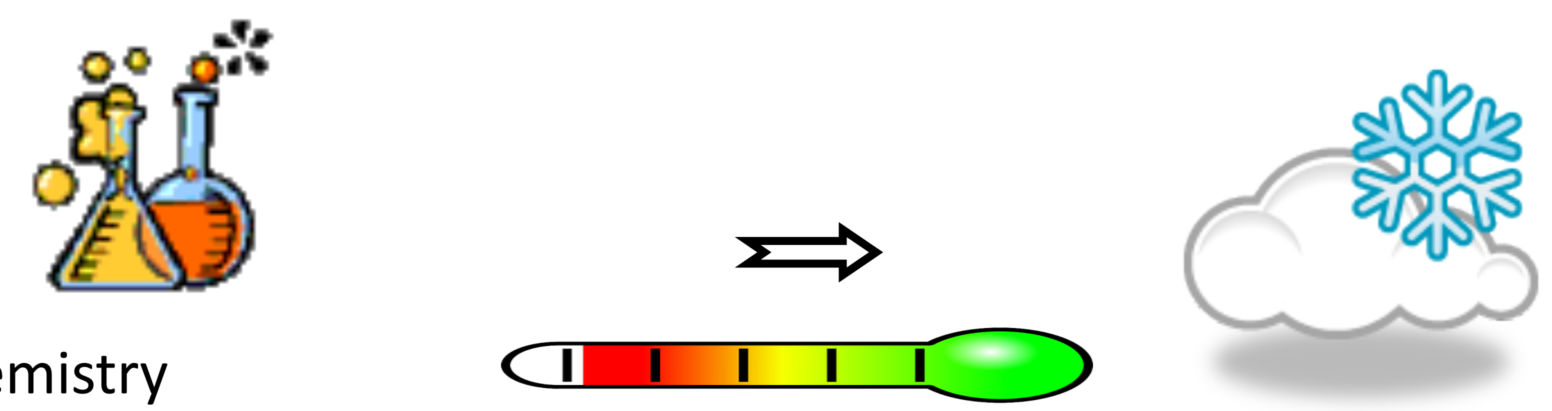
Advance in cooling of large molecules

Cooling

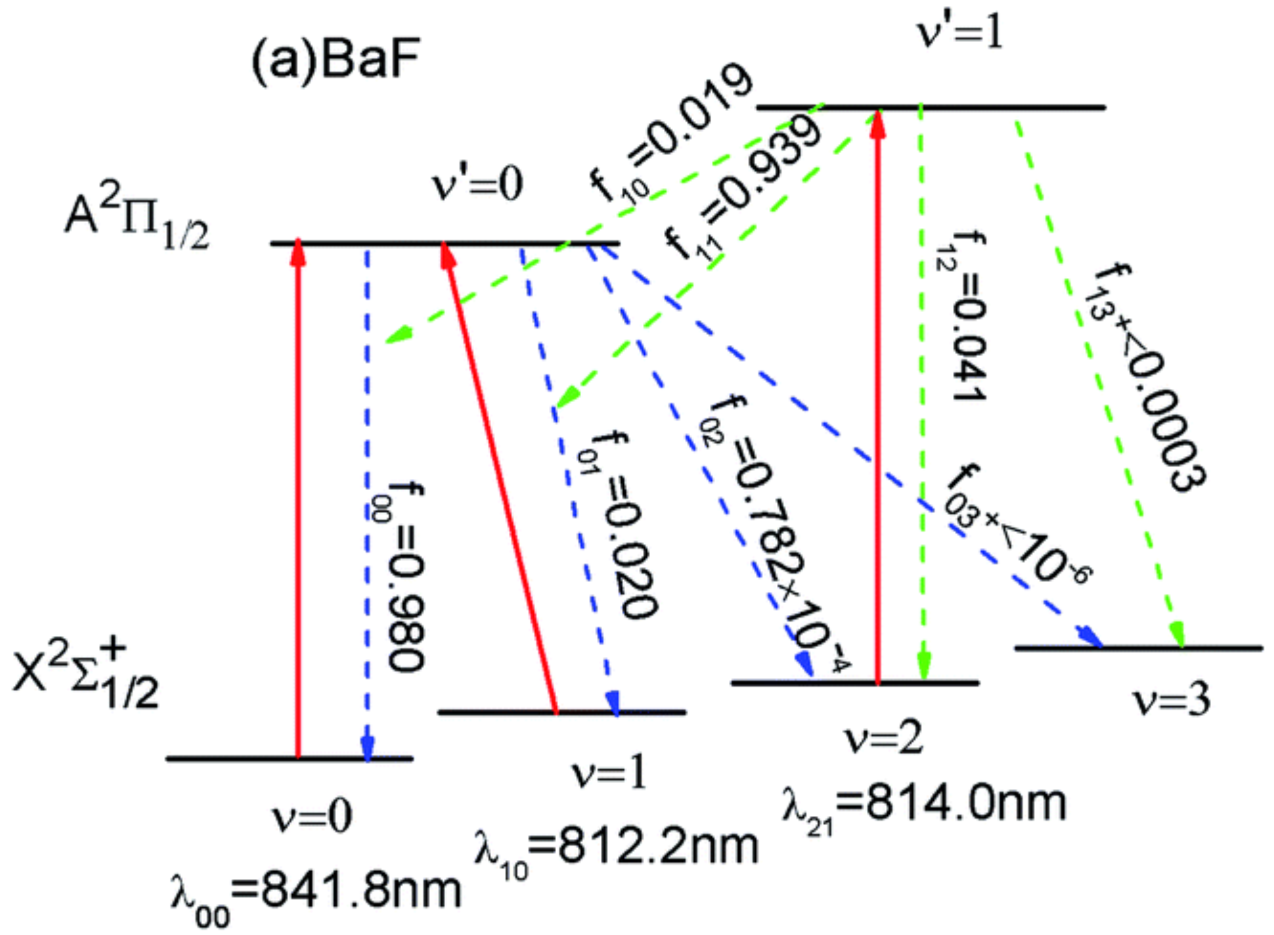


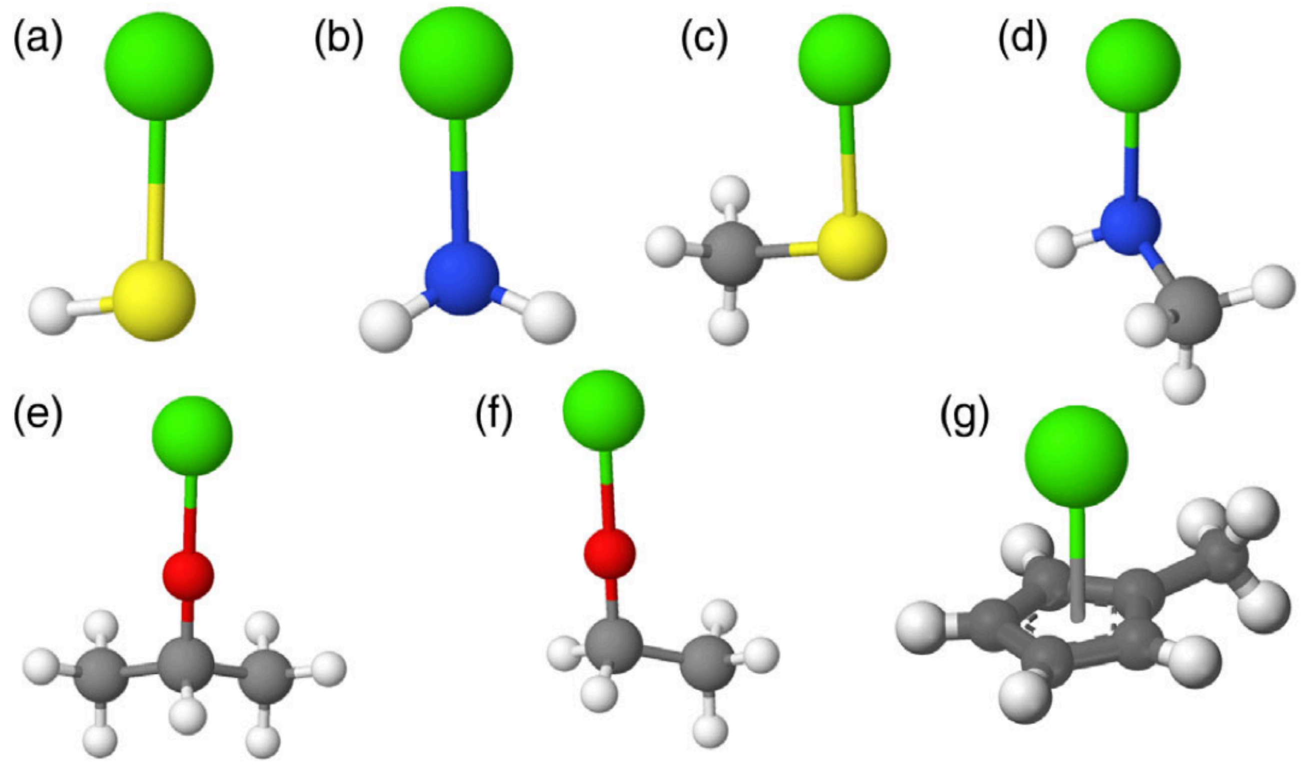
Chemistry
(Prepare molecules)

T = 1 mK
n ~ $10^8/cm^3$

Stark decelerator: very fast ground state molecule thanks to buffer gas cooling, but one have to brake them…

- Alkali-like molecules (one electron localised on one side)





Molecular Asymmetry and Optical Cycling: Laser Cooling Asymmetric Top Molecules

Benjamin L. Augenbraun,[1,2,*] John M. Doyle,[1,2] Tanya Zelevinsky,[3] and Ivan Kozyryev[3,†]

Advance in cooling of large molecules

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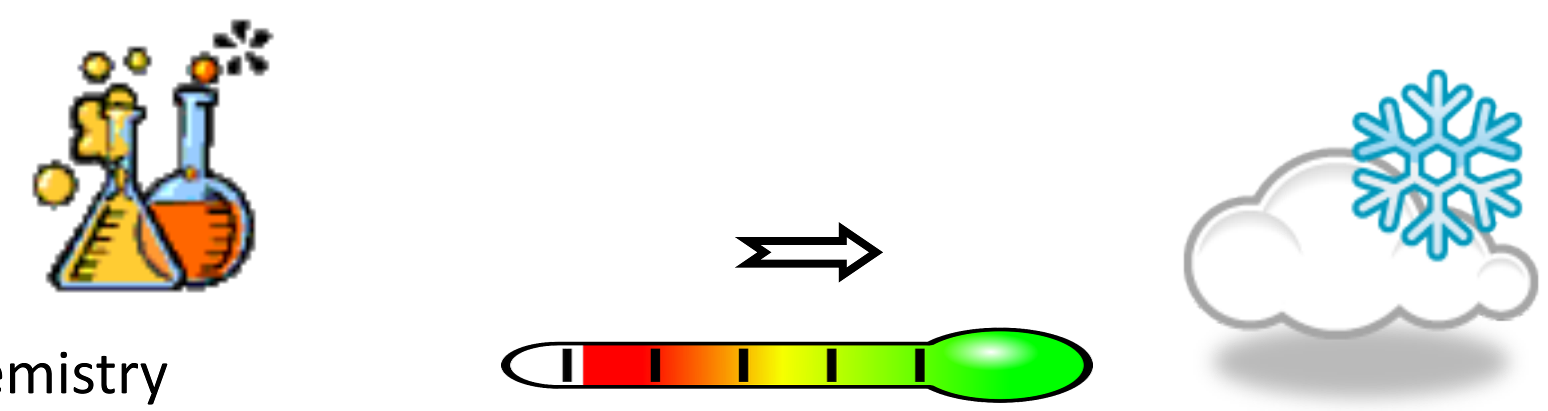
Cooling



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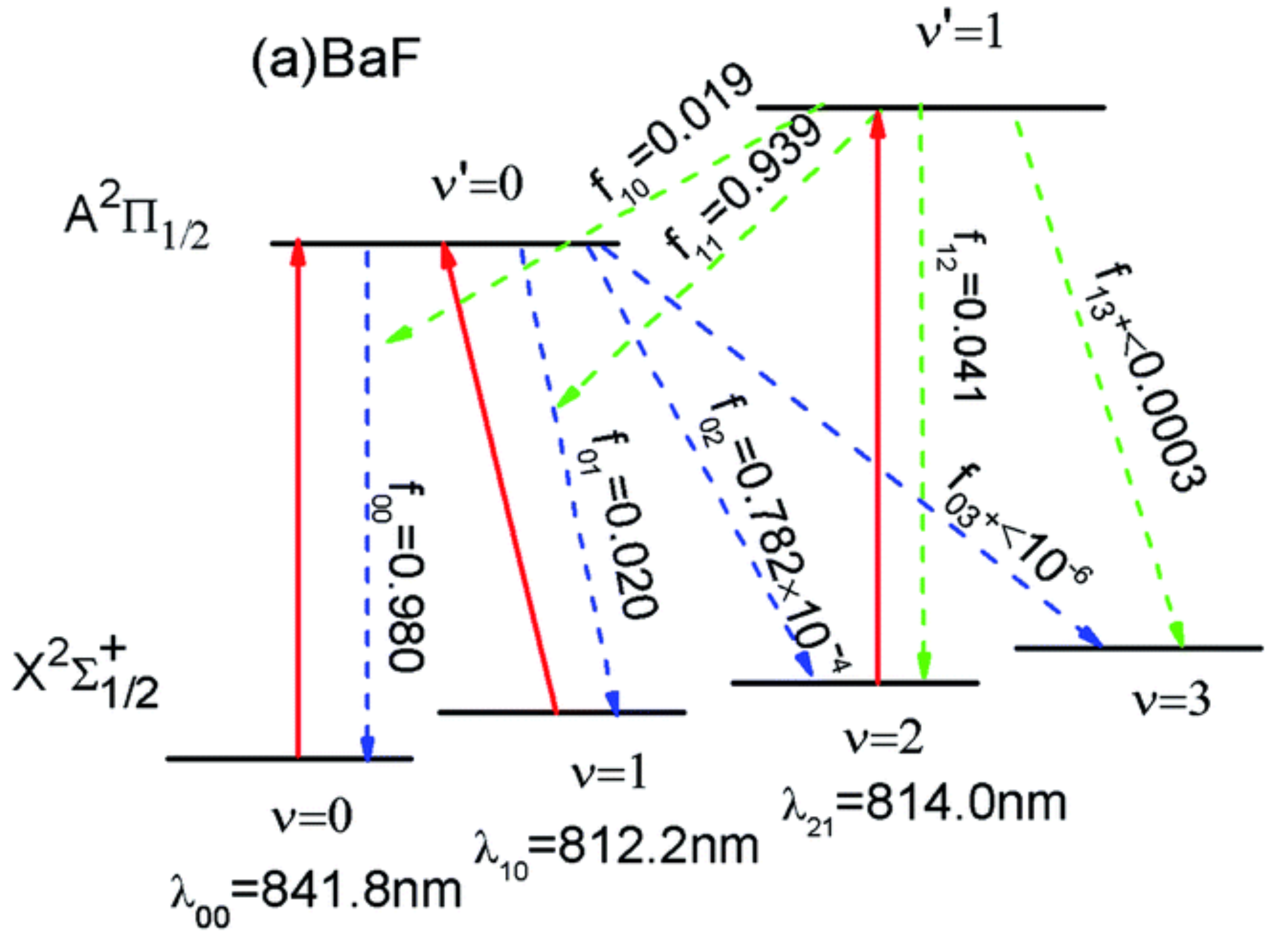

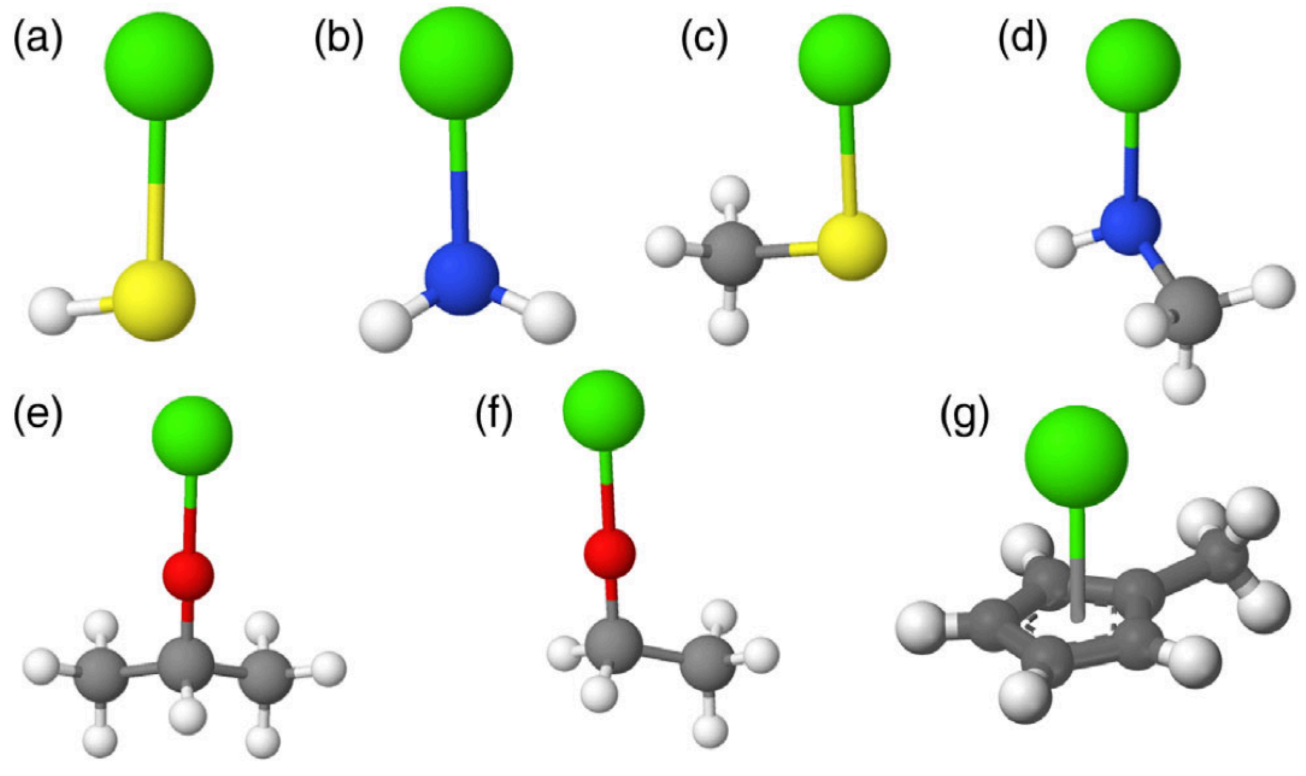

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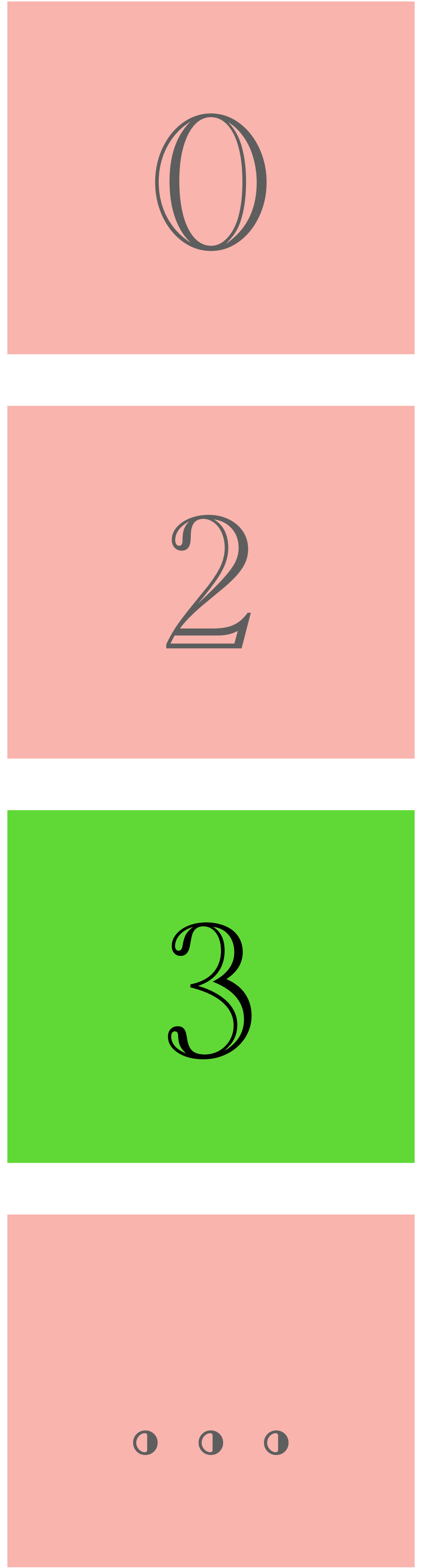
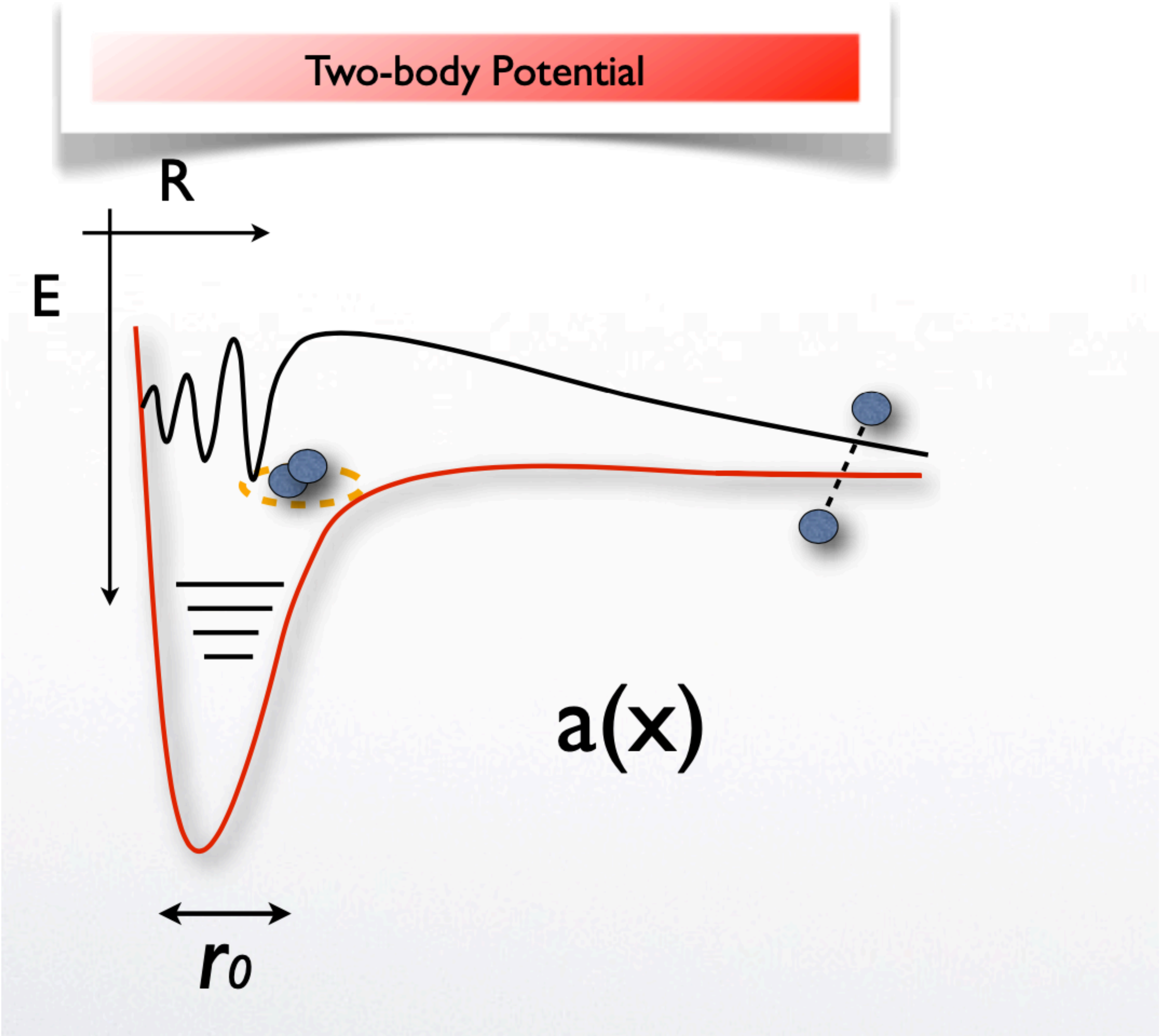
Three-body: The origin of the problem



- Classical problem has solutions only for special cases (one of the participant is small, Lagrange points)

- Quantum case: ^{3}He, deuteron and adrons. No tuning knobs



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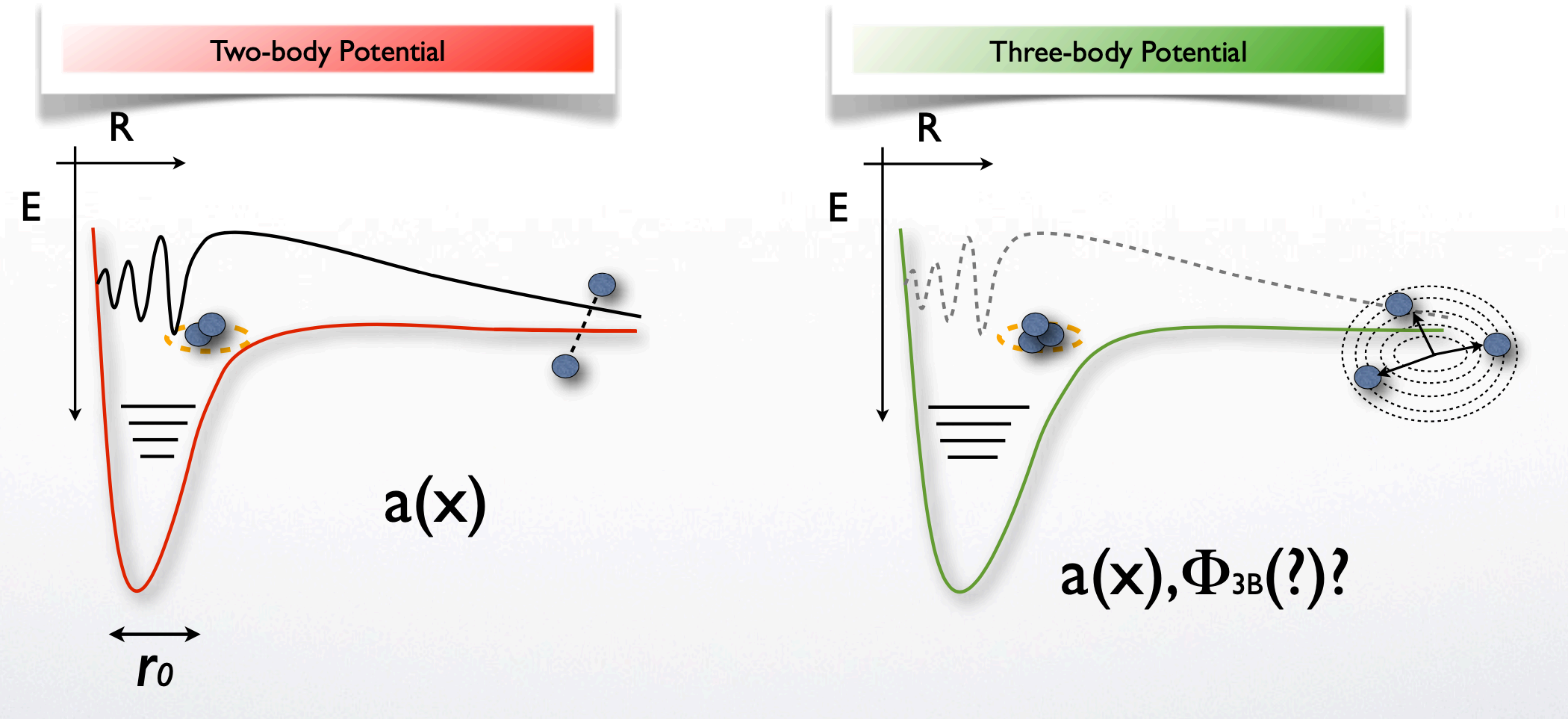

Efimov state

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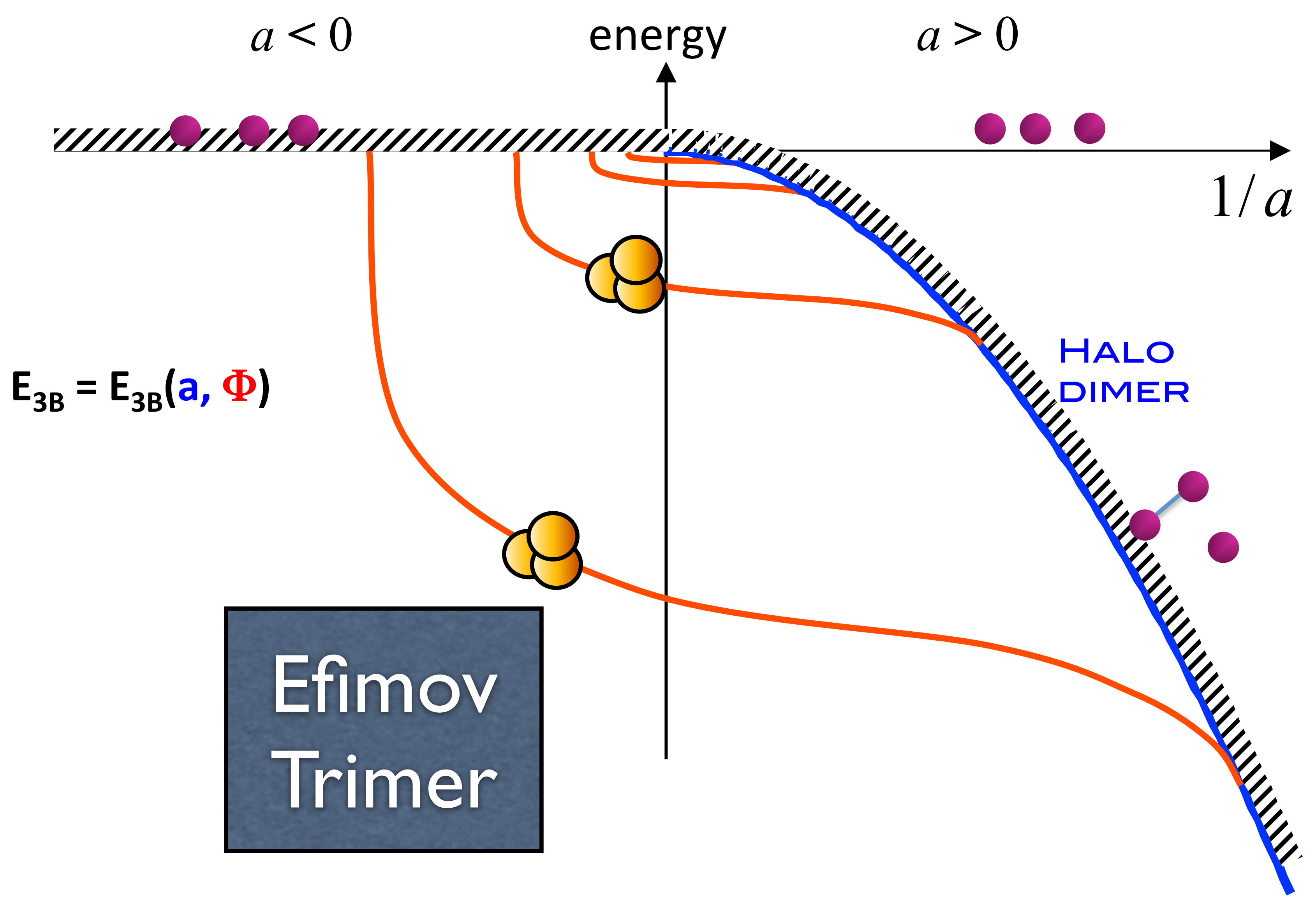
Efimov considered very large scattering length



Efimov, V. (1970). "Energy levels arising from resonant two-body forces in a three-body system". *Physics Letters B*. **33** (8): 563–564.

Efimov state

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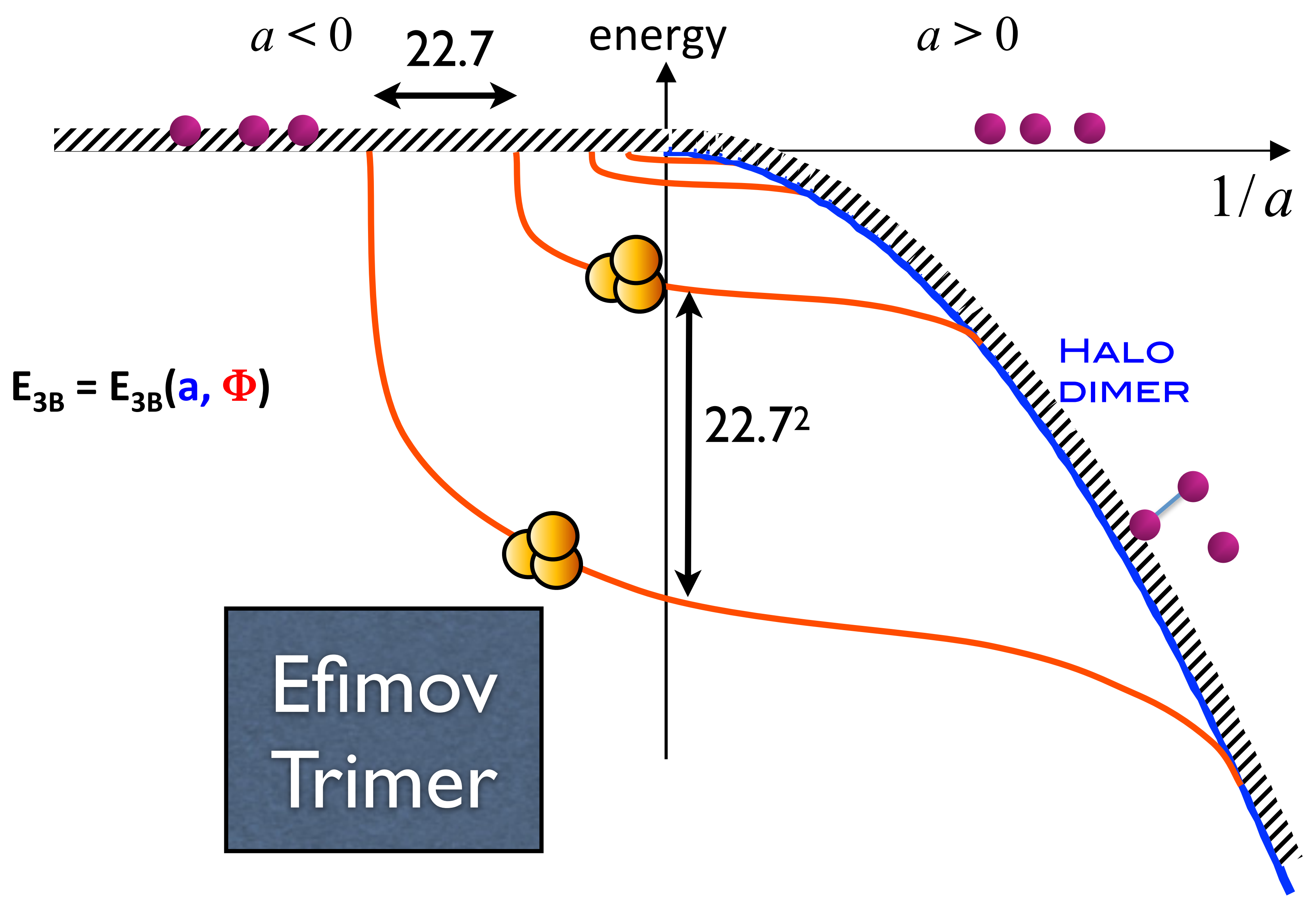
Efimov considered very large scattering length



Efimov, V. (1970). "Energy levels arising from resonant two-body forces in a three-body system". *Physics Letters B*. **33** (8): 563–564.

Efimov state

0

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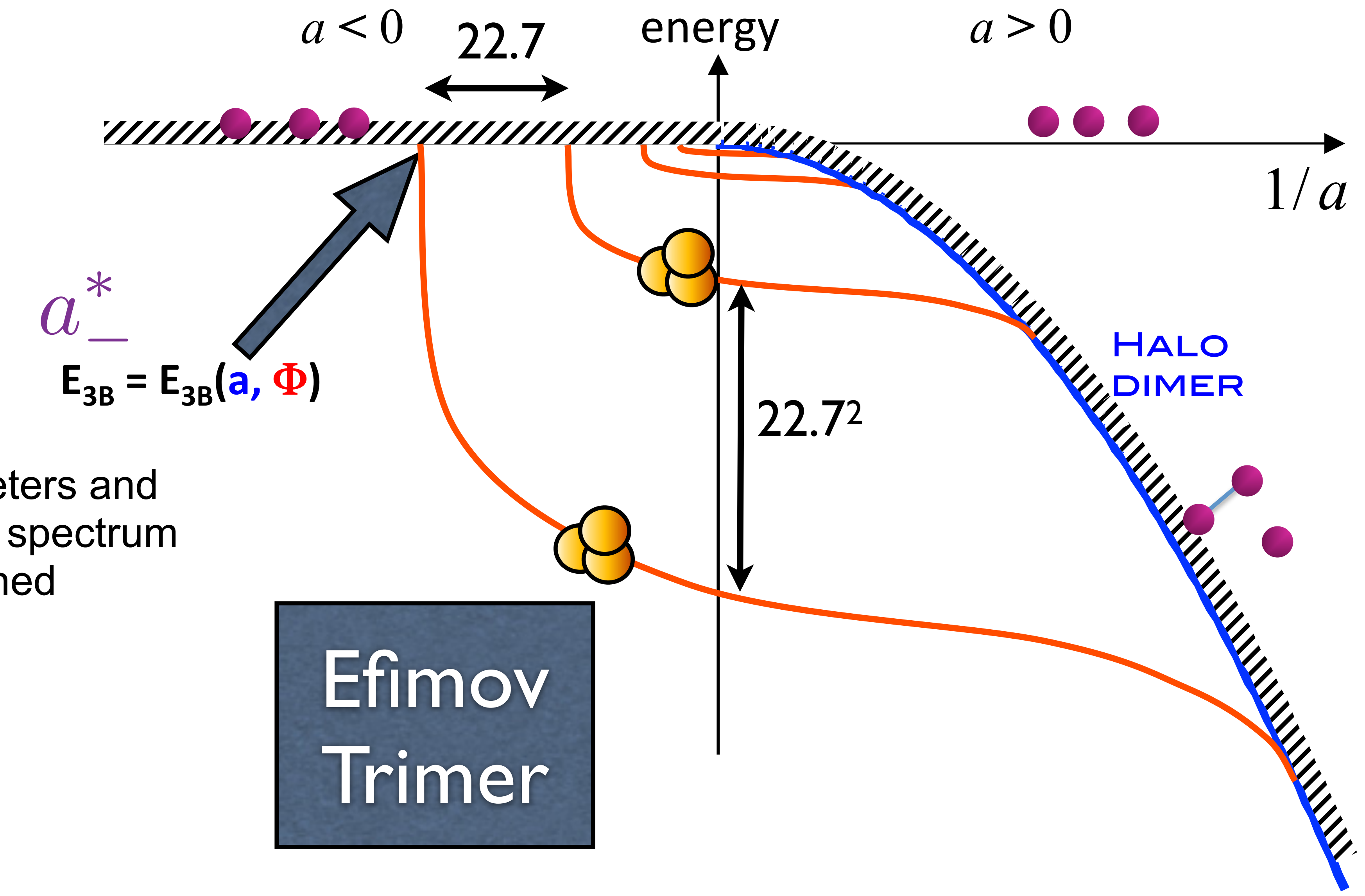

One parameters and the complete spectrum is defined

Efimov, V. (1970). "Energy levels arising from resonant two-body forces in a three-body system". *Physics Letters B*. **33** (8): 563–564.

Efimov state

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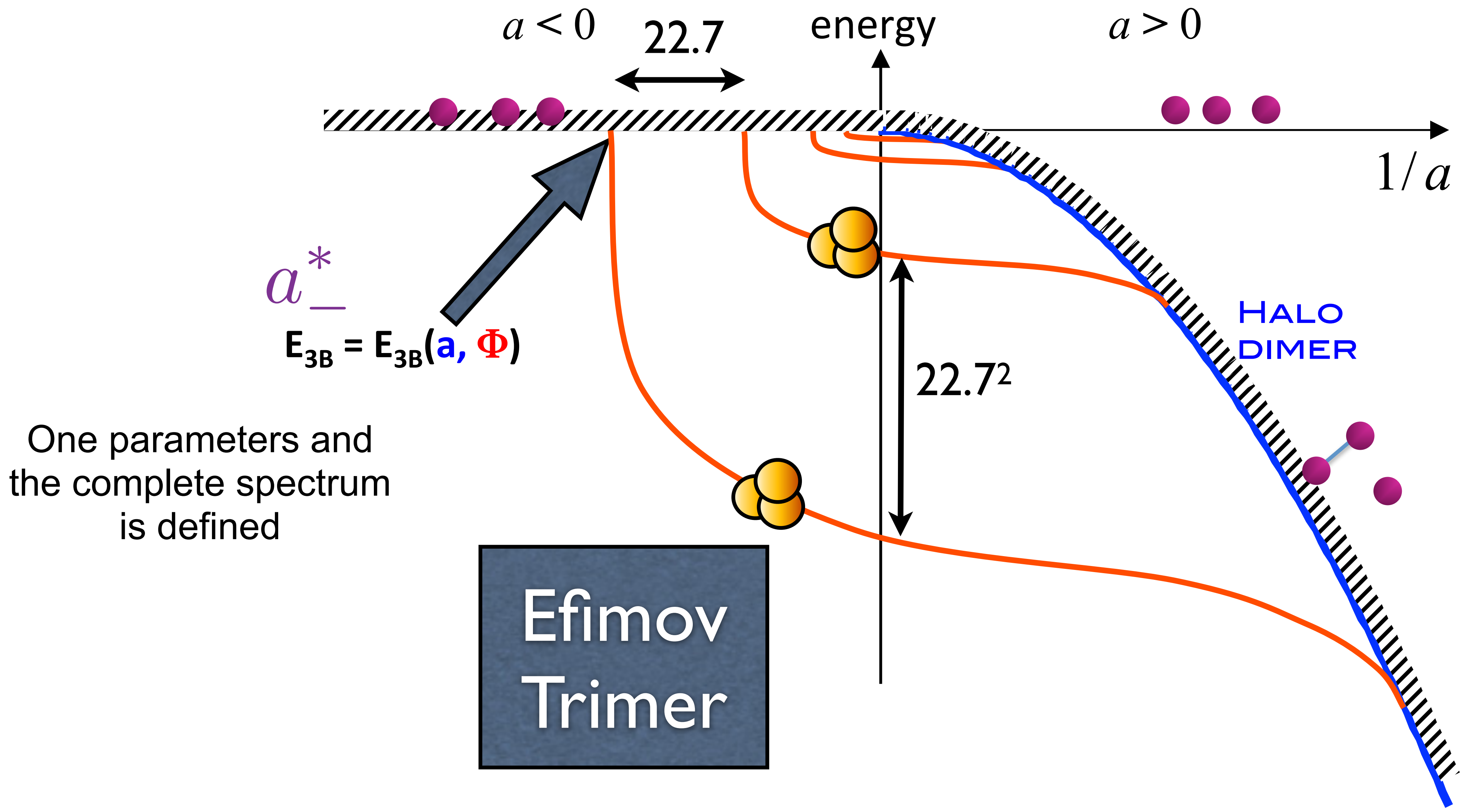

Long lasting search in helium droplets, halo nuclei…

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Efimov state

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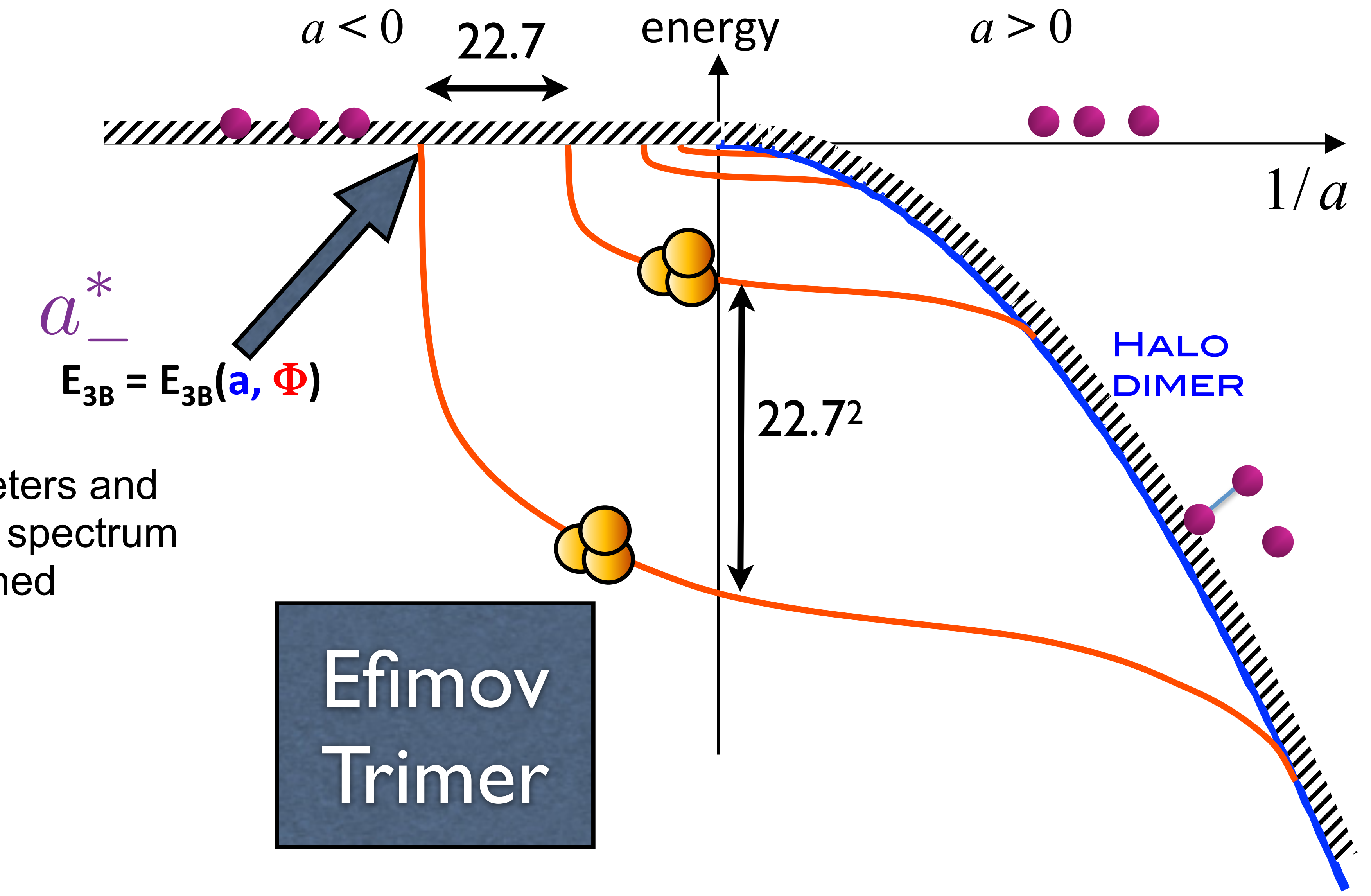

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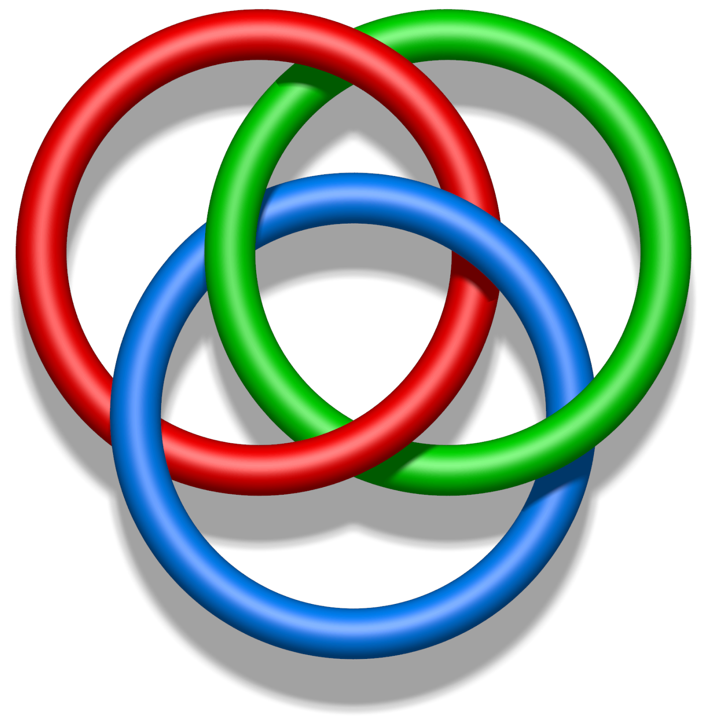

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Three-body states and losses

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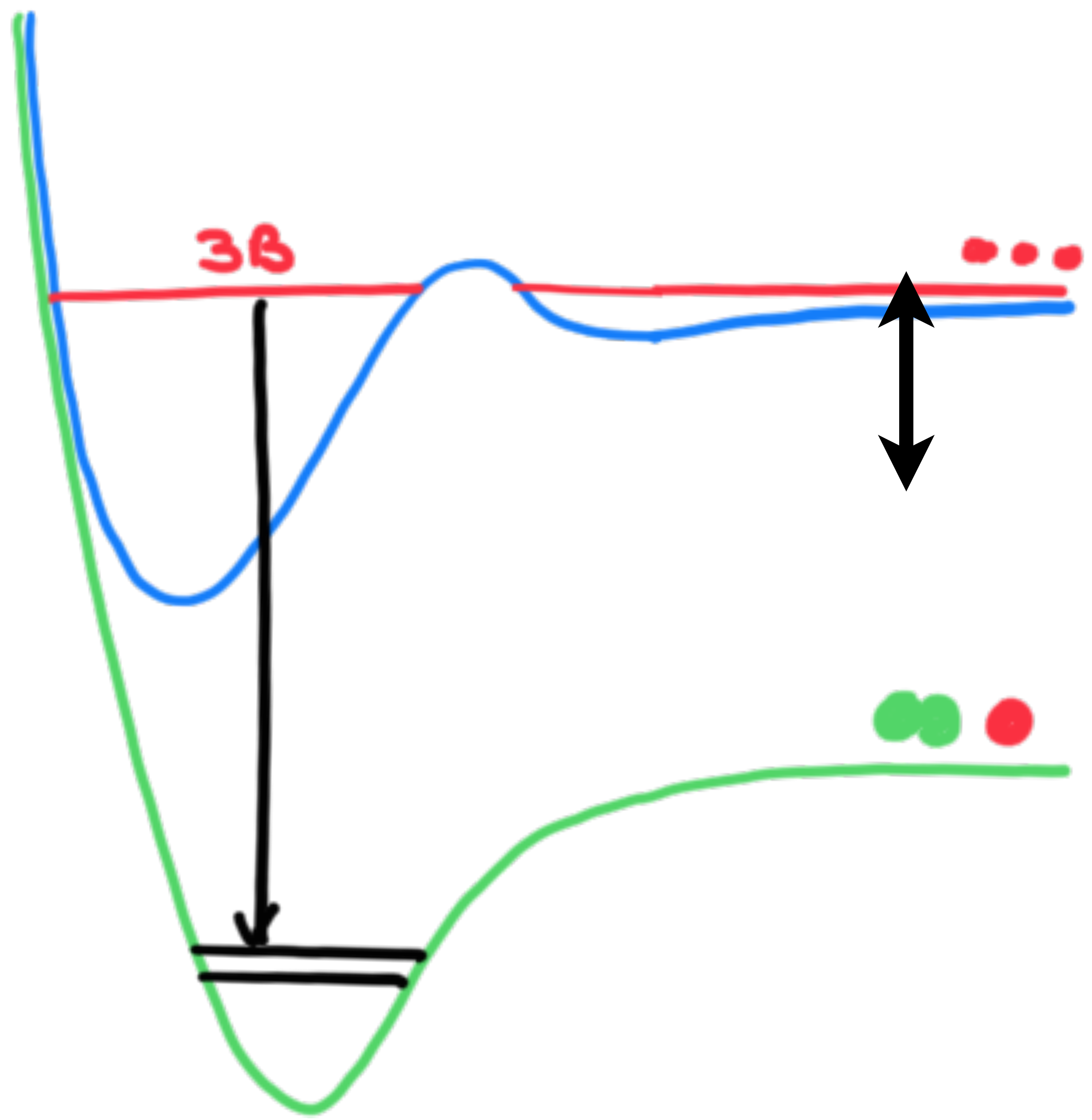
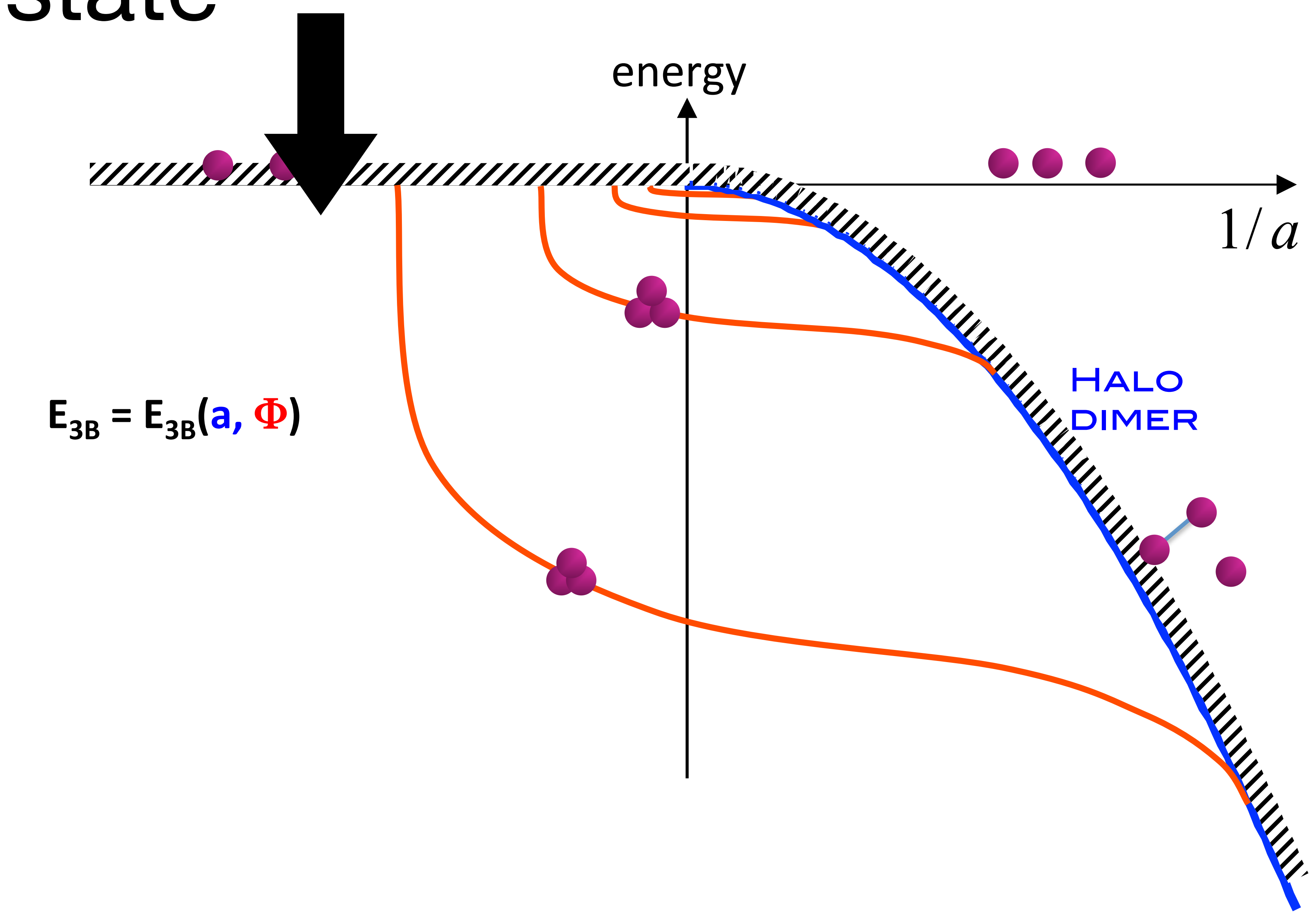
. . .

- Efimov state is behind a centrifugal barrier
- We can tune entrance by changing the scattering length (i.e. the energy of the entering atoms)
- What enters decay fast into low lying molecular state





Three-body states and losses

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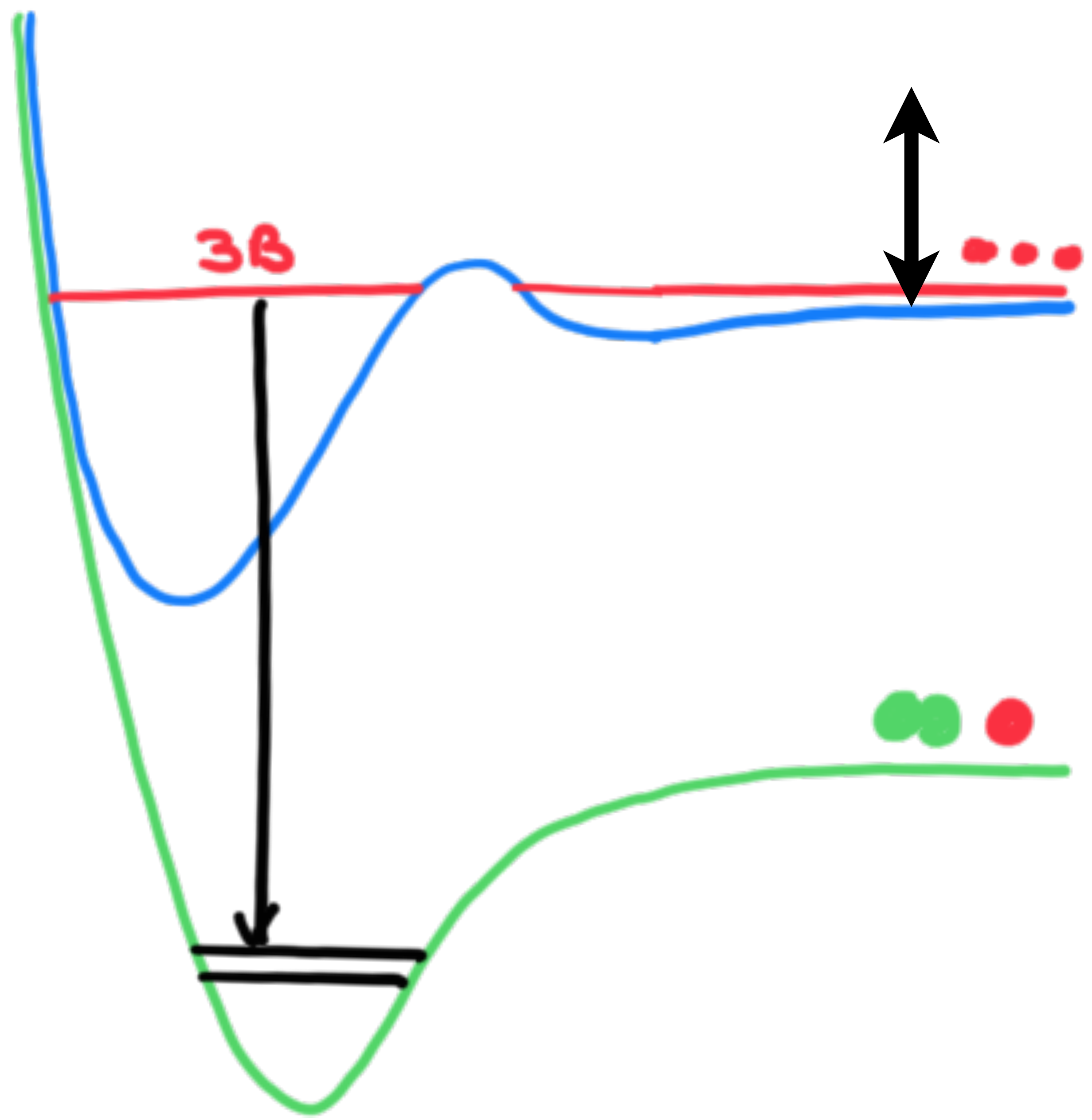

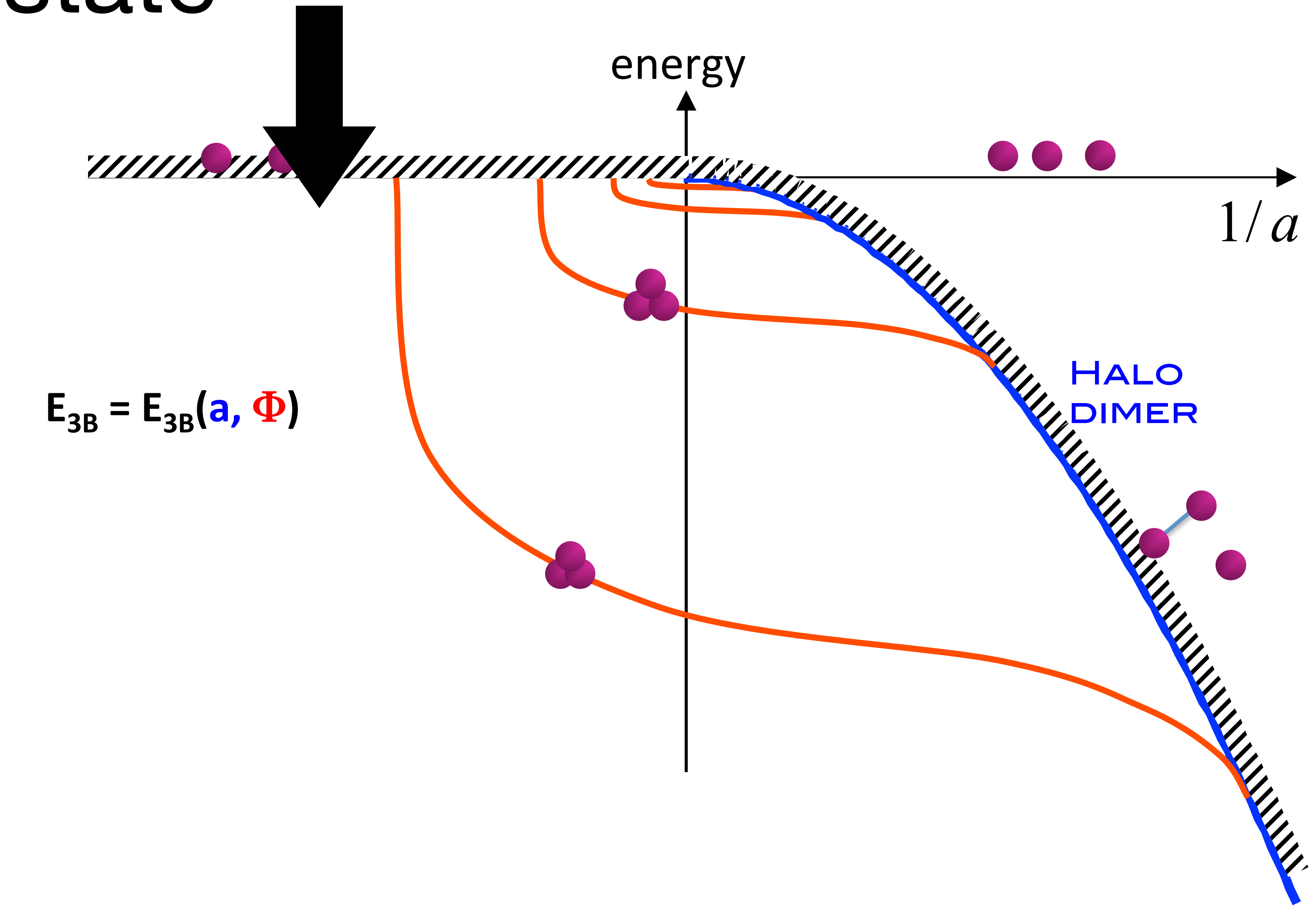

Three-body states and losses

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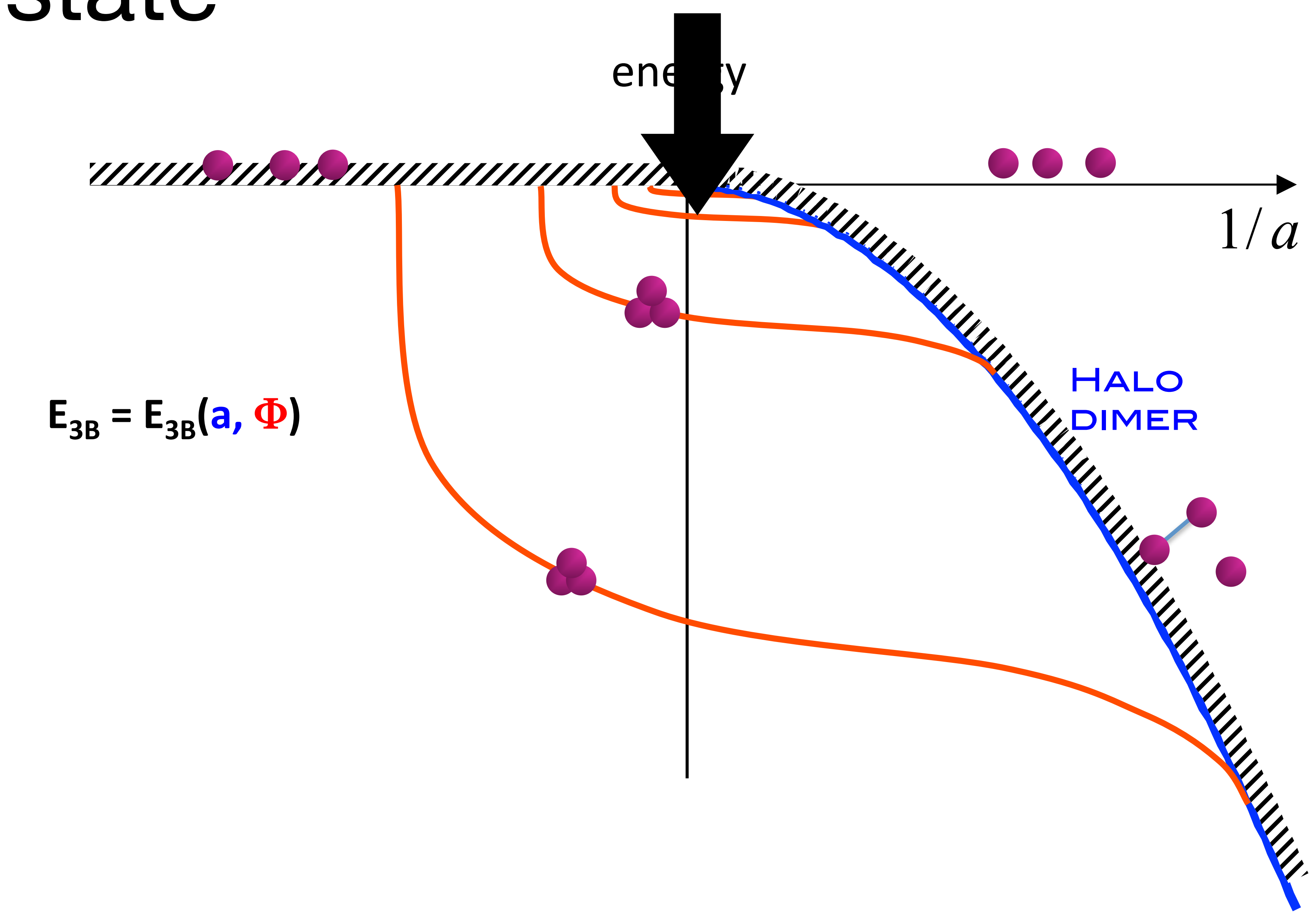

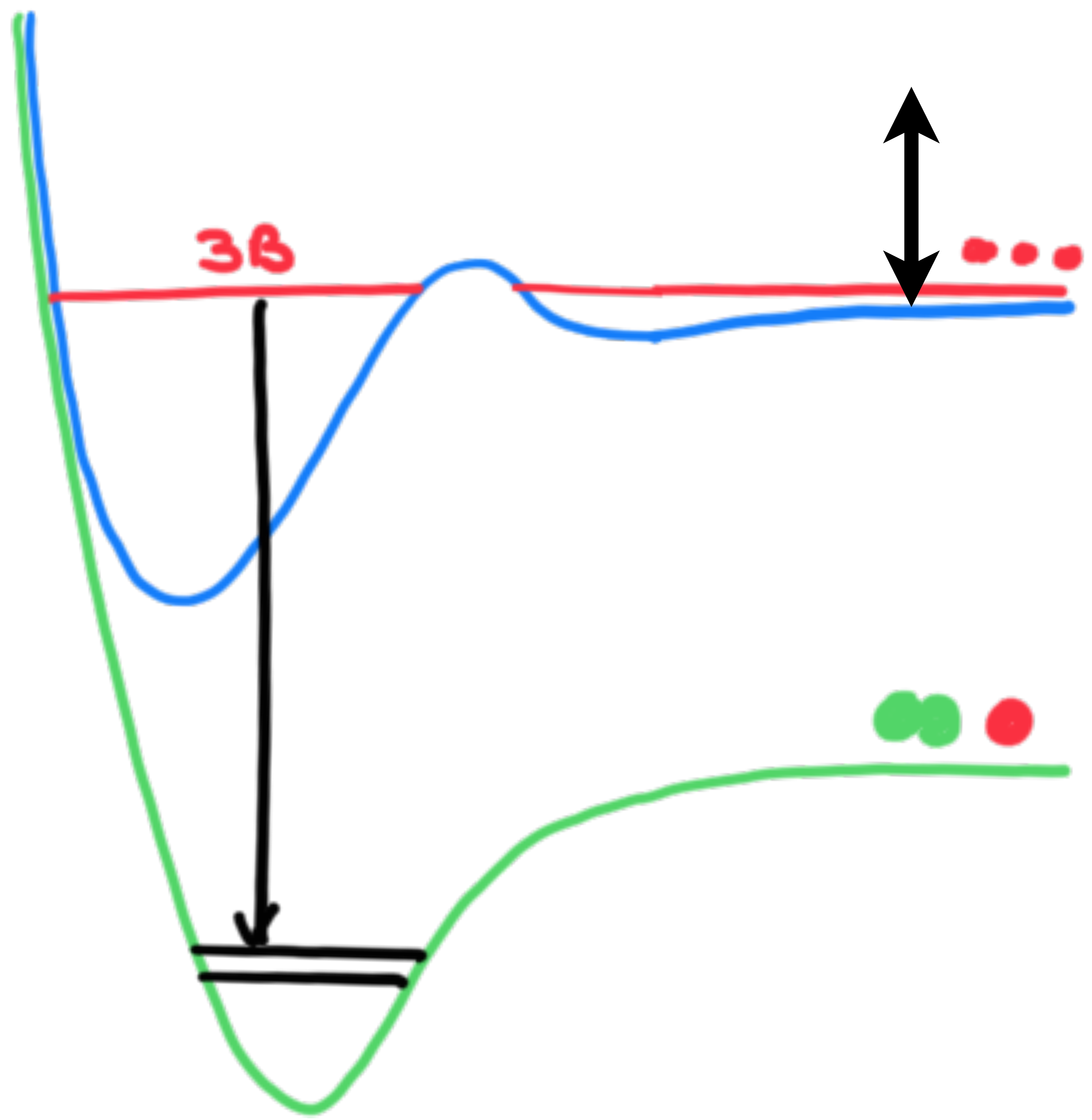

Three-body states and losses

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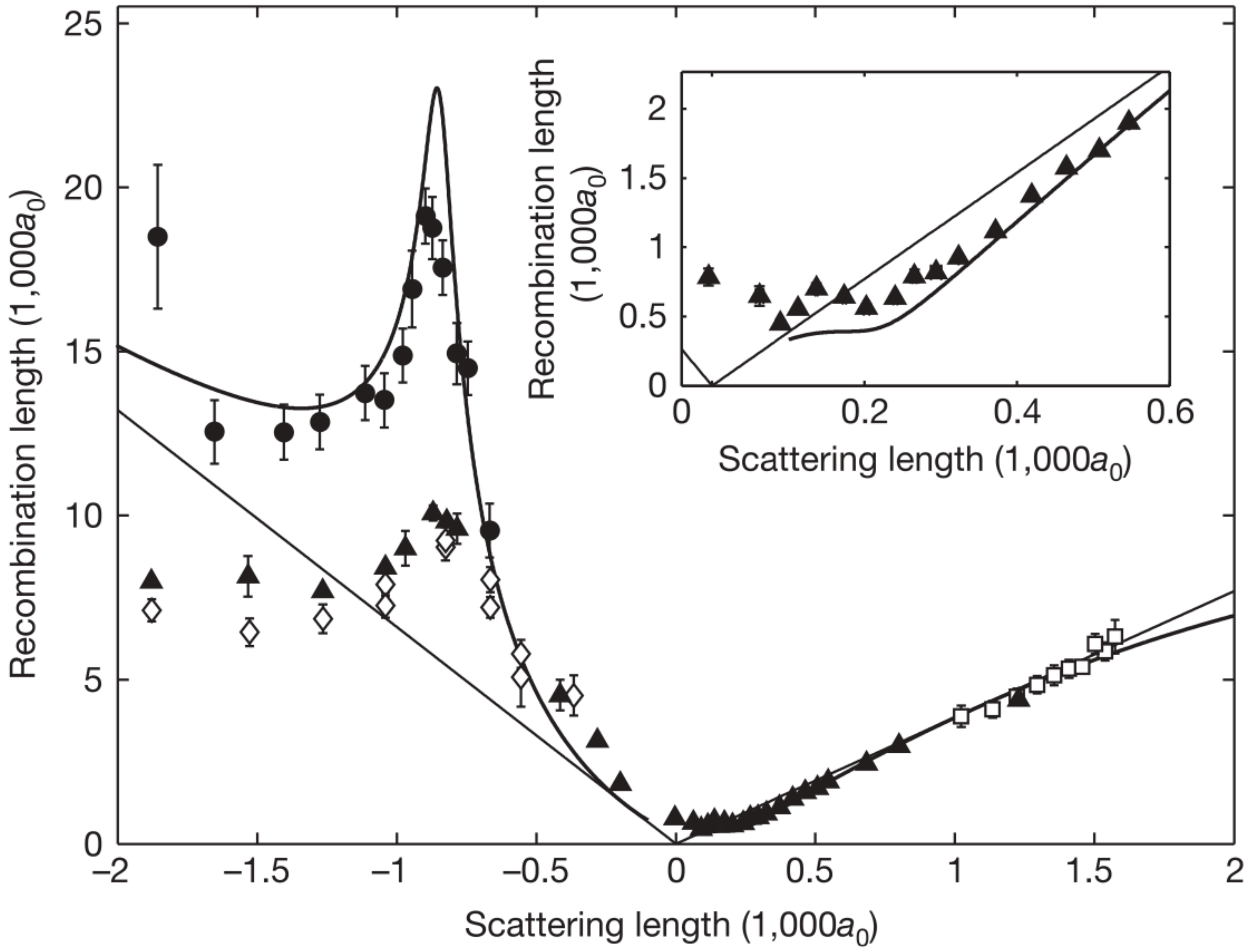

Innsbruck 2006

T. Kraemer et al (2006). "Evidence for Efimov quantum states in an ultracold gas of caesium atoms". *Nature*. **440** (7082): 315–318

2+1 and Efimov state association

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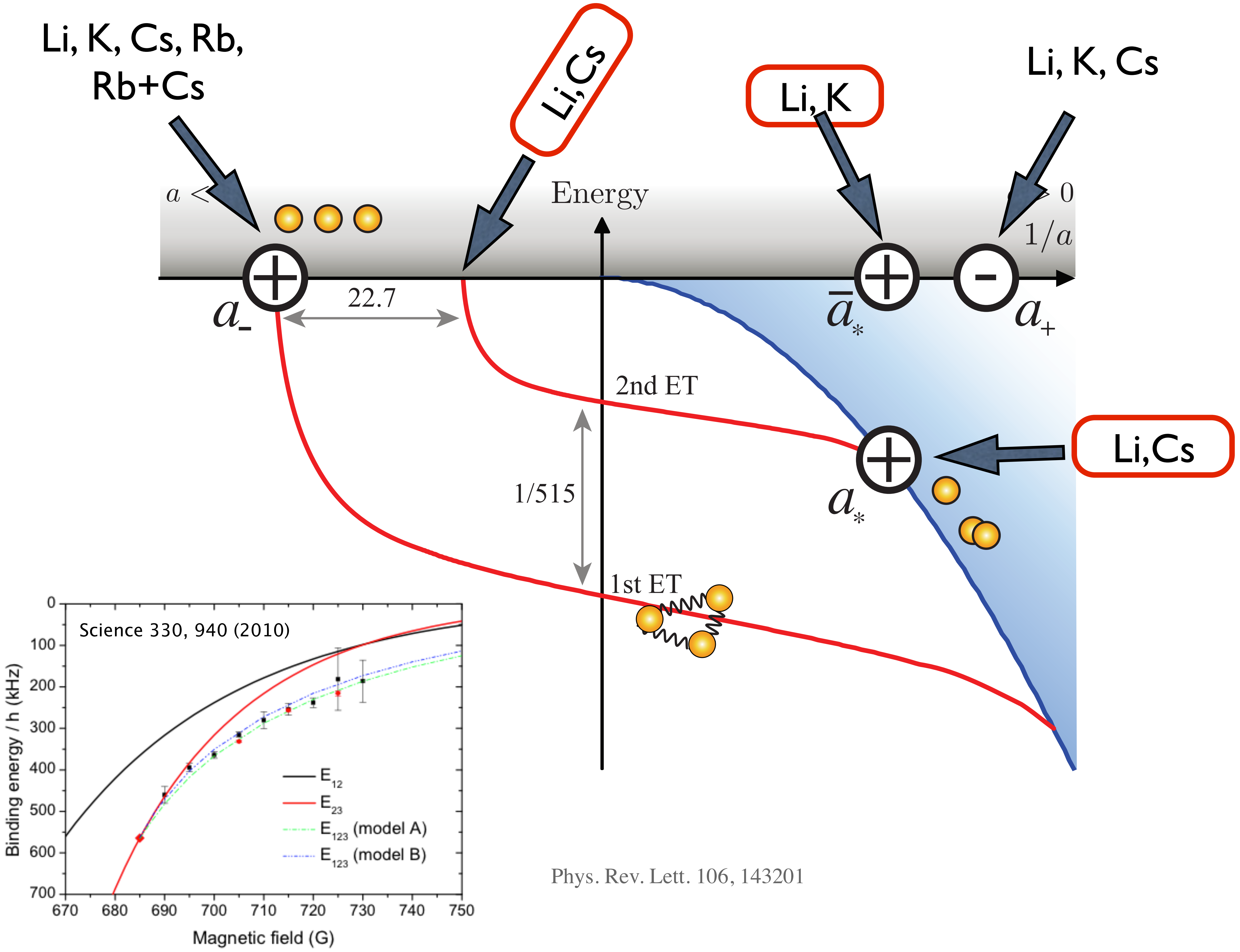

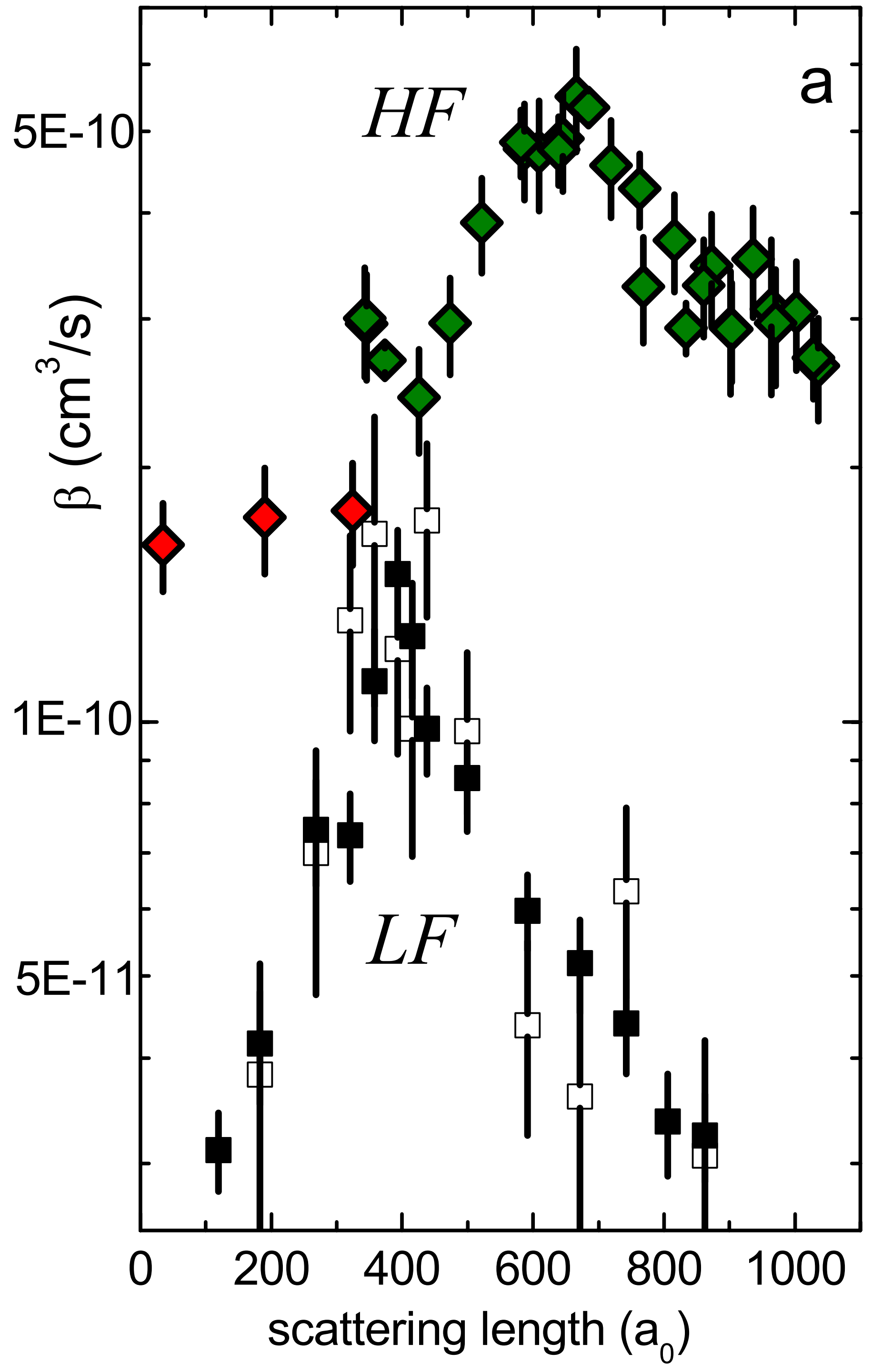

2+1 and Efimov state association

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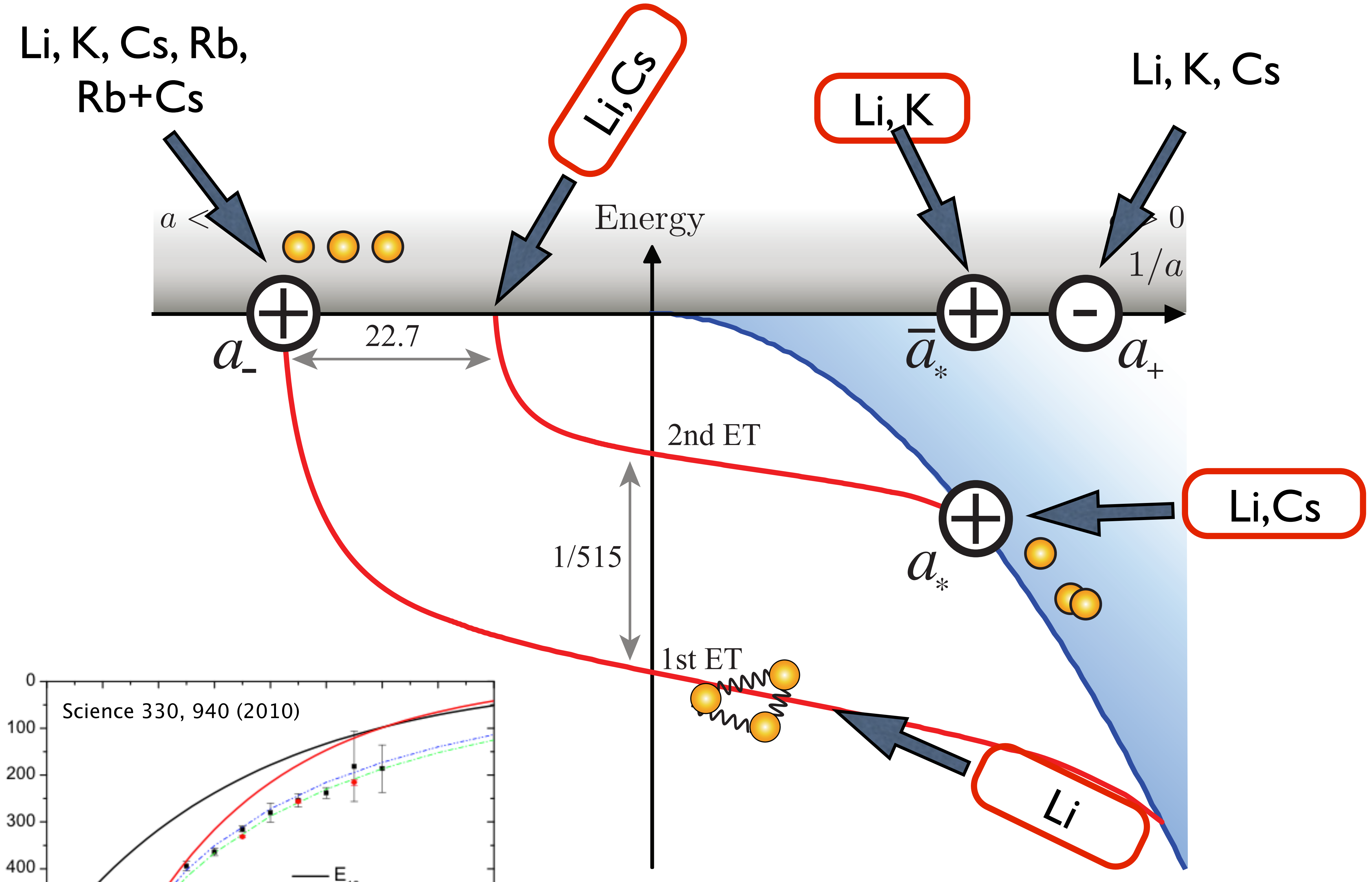
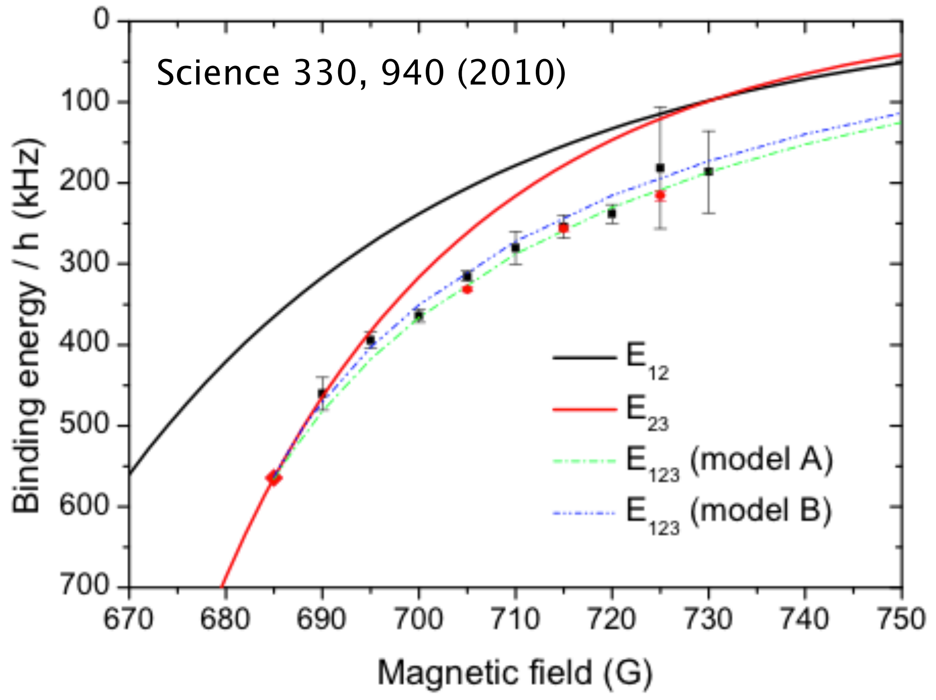
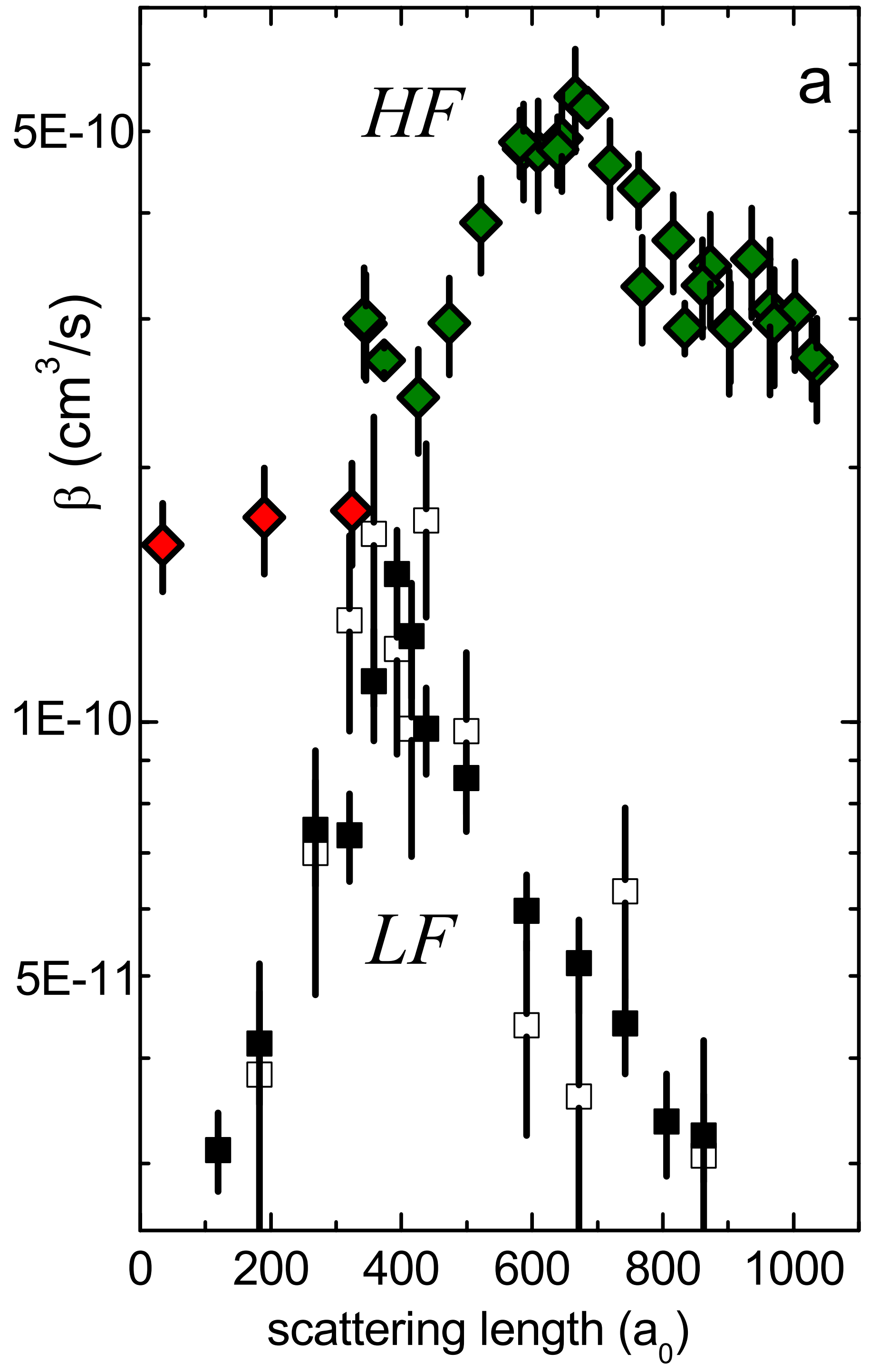




Phys. Rev. Lett. 106, 143201



Universality

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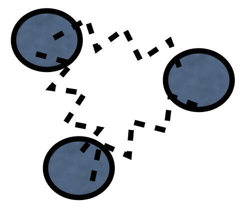
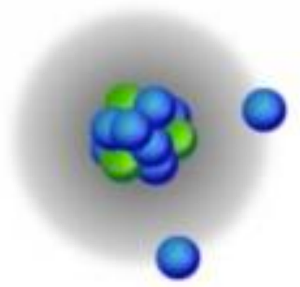
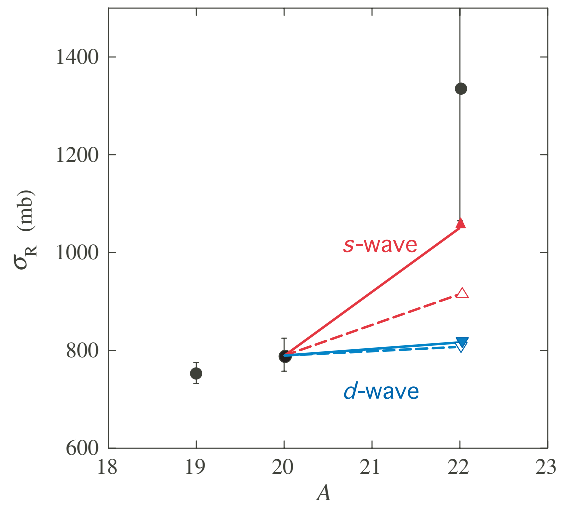
Cold atoms and droplets

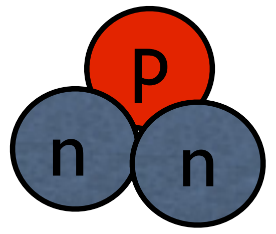


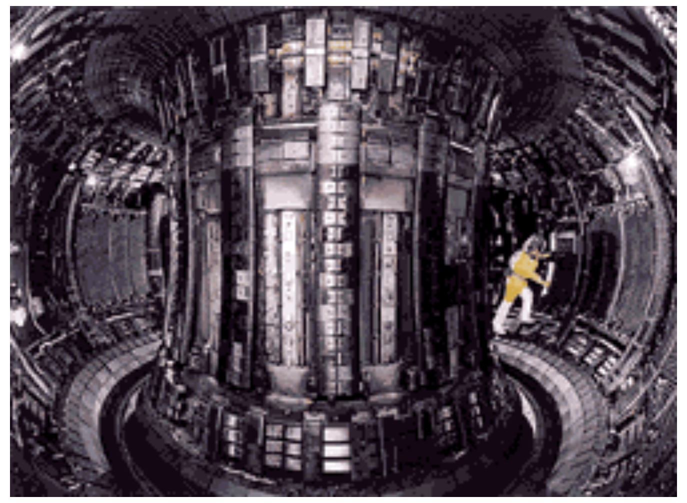
^{22}C

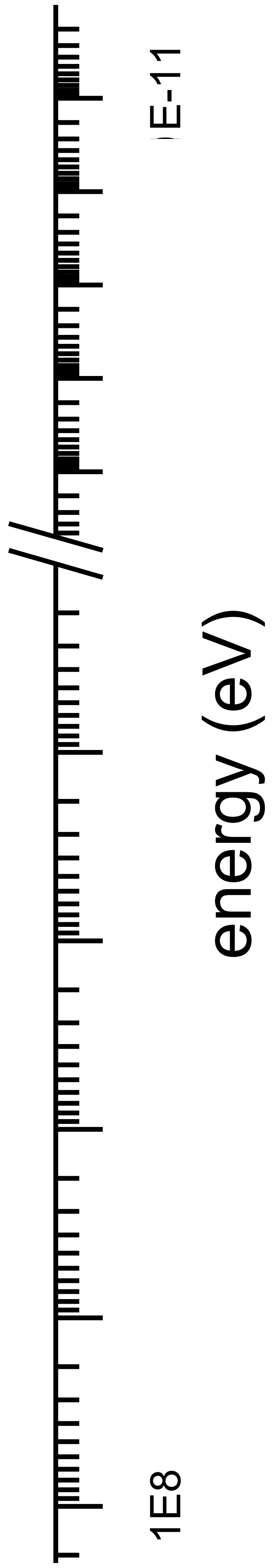




Triton







Universality

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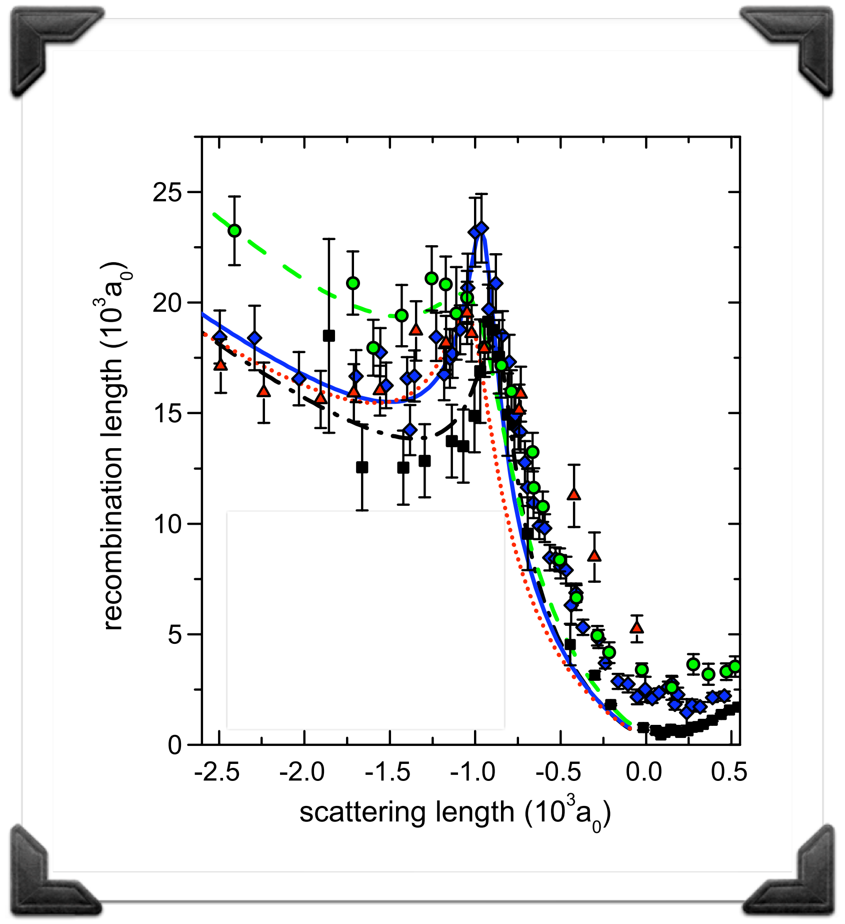
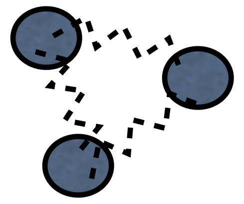


- Same atoms different FR

Cold atoms and droplets



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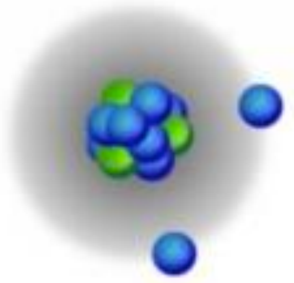
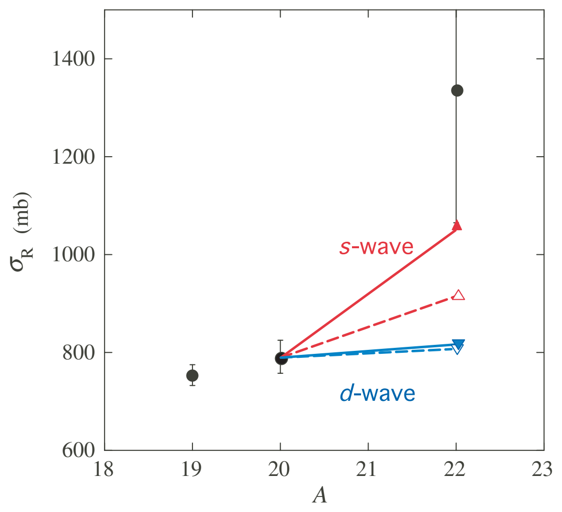
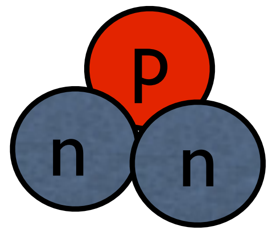
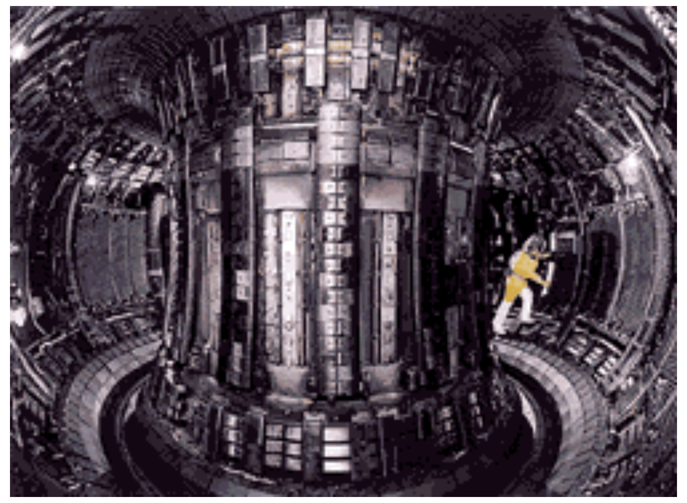
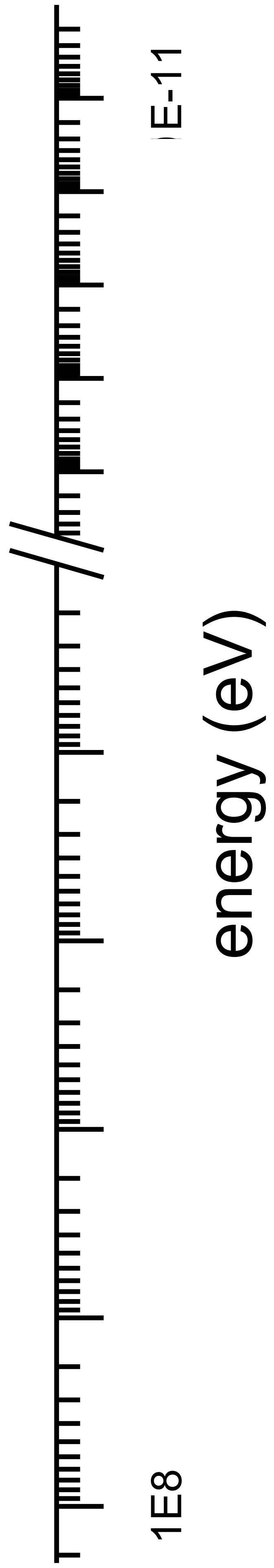




Triton







Universality

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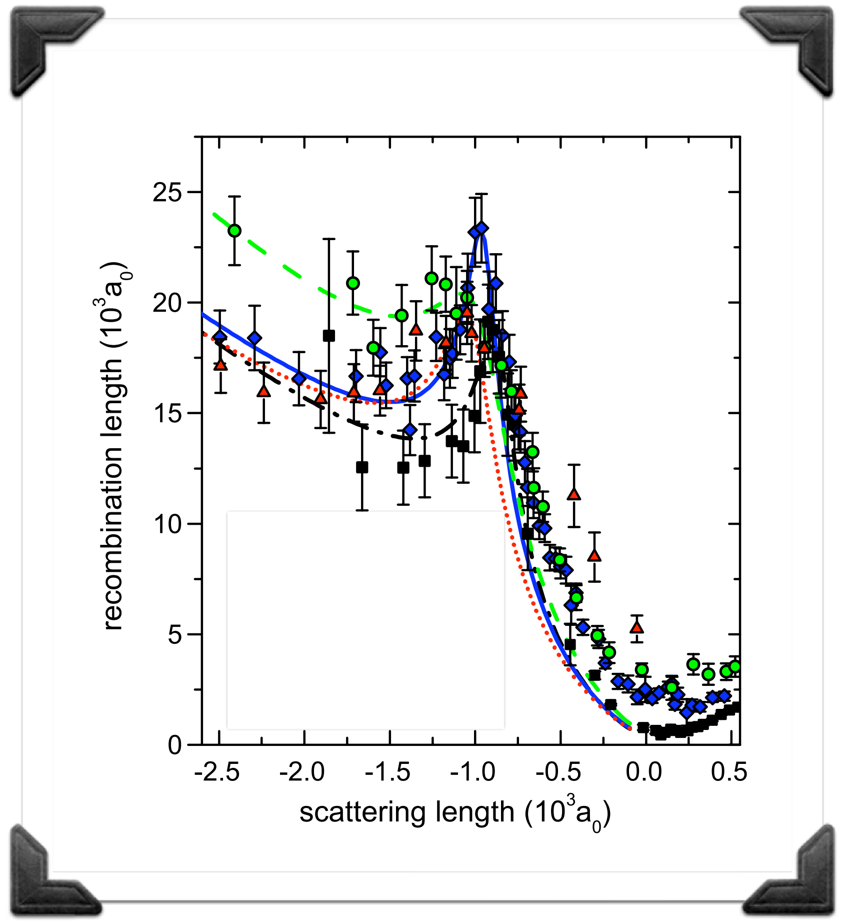
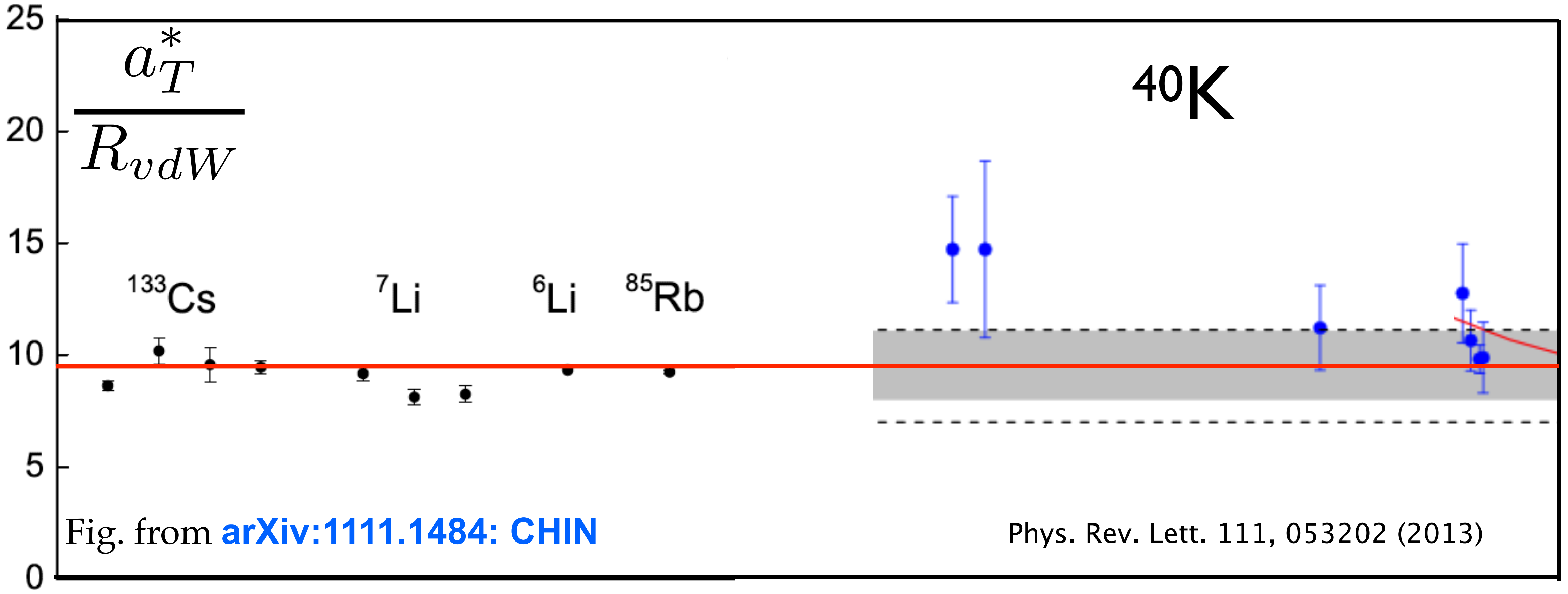


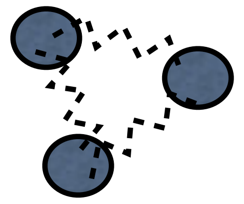
- Same atoms different FR

- Different atoms

a_T^* ~ 9-10 R_{VdW}



Cold atoms and droplets



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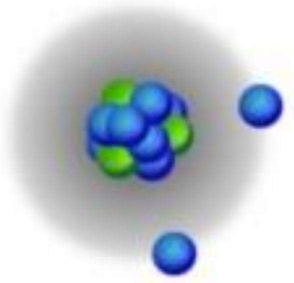
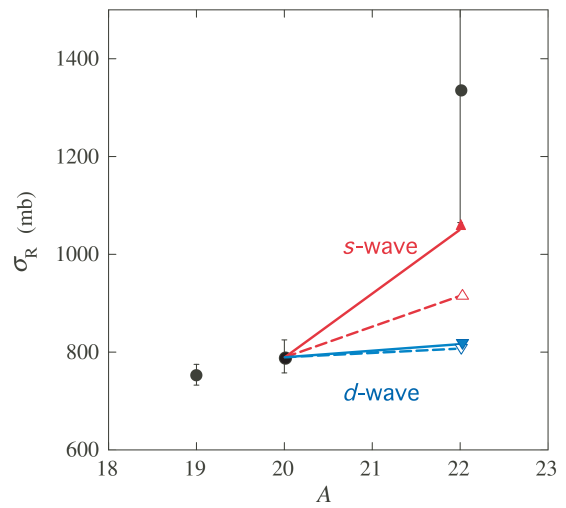
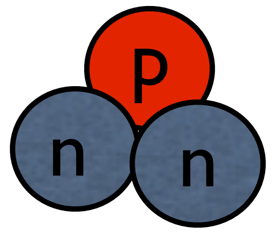
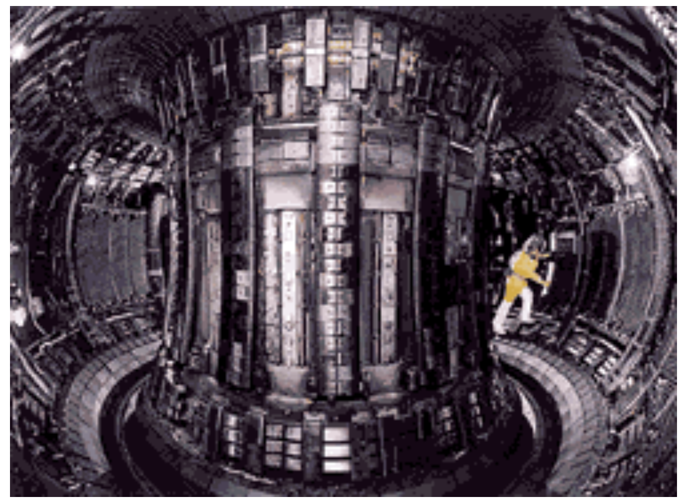
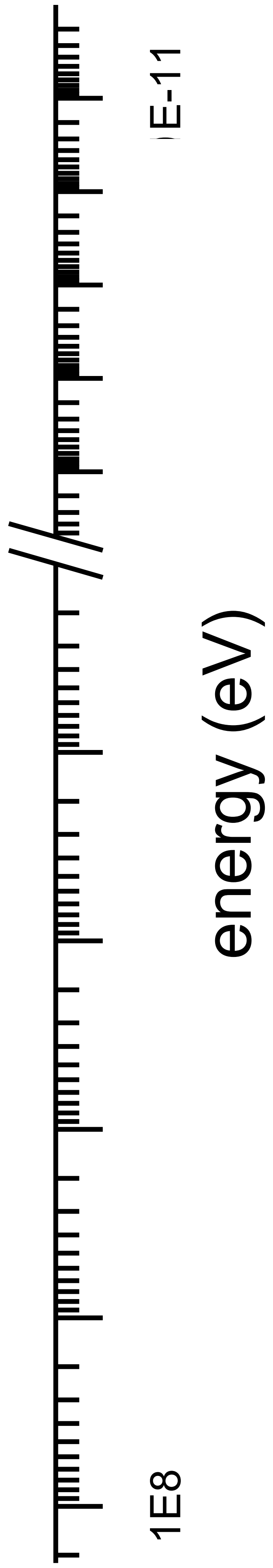




Triton







Extension to four- and more body states

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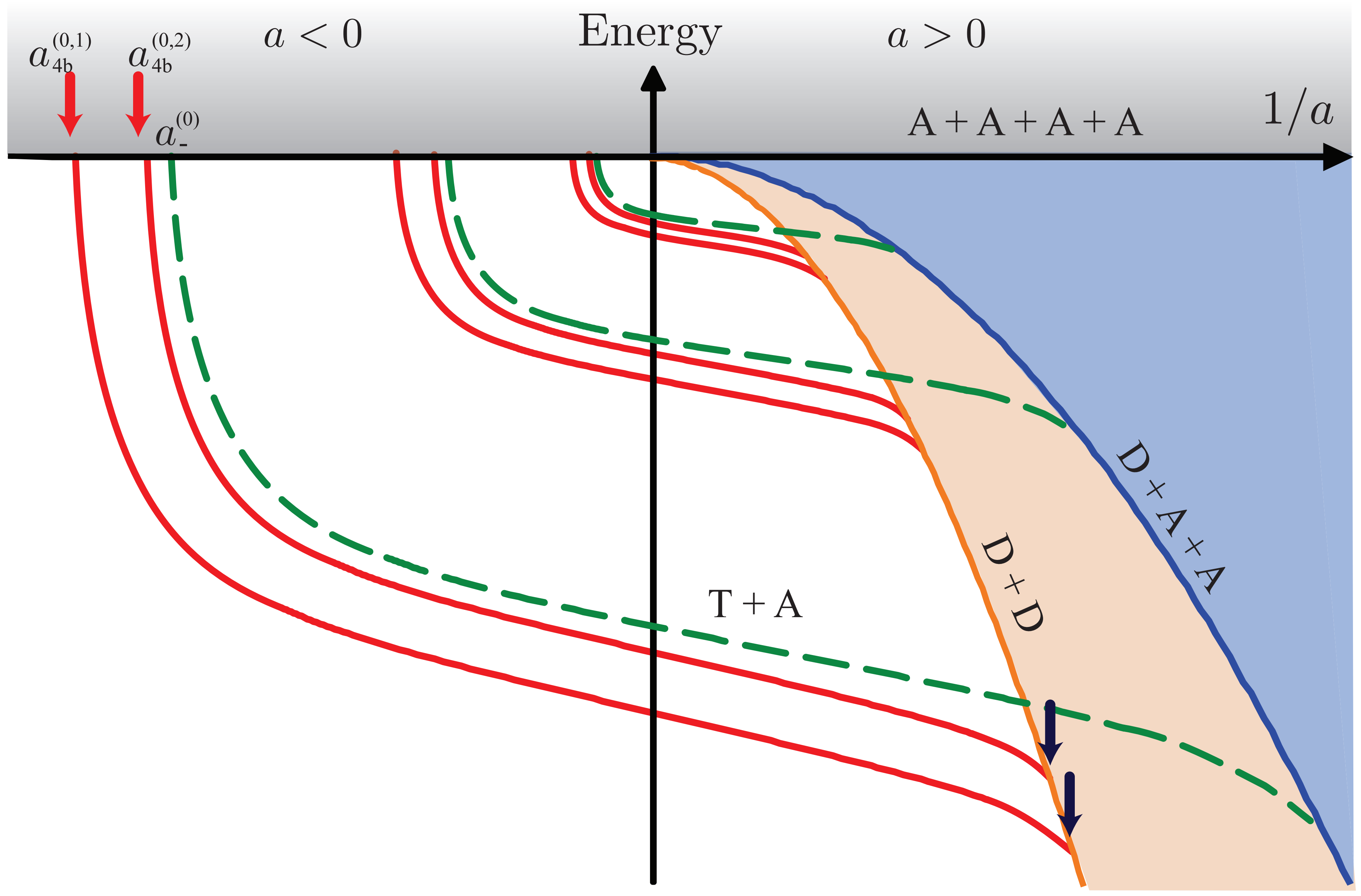
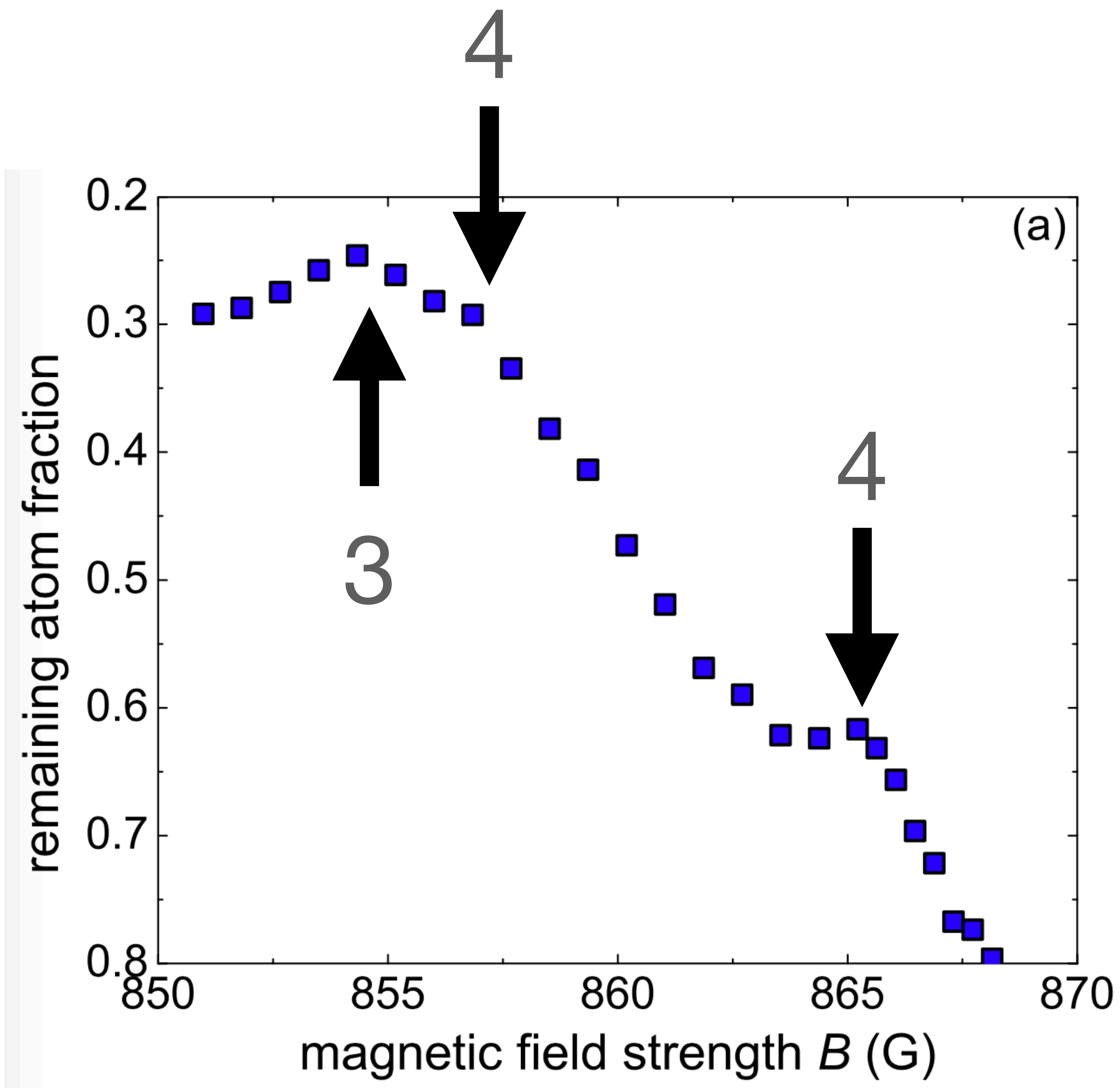
- Immanuel Kant: At dinner, never more than the Muses (9) or less than the Fates (3)
- Interest to connect few to many boys state
- Connection to high energy physics (tetra- and penta-quark)



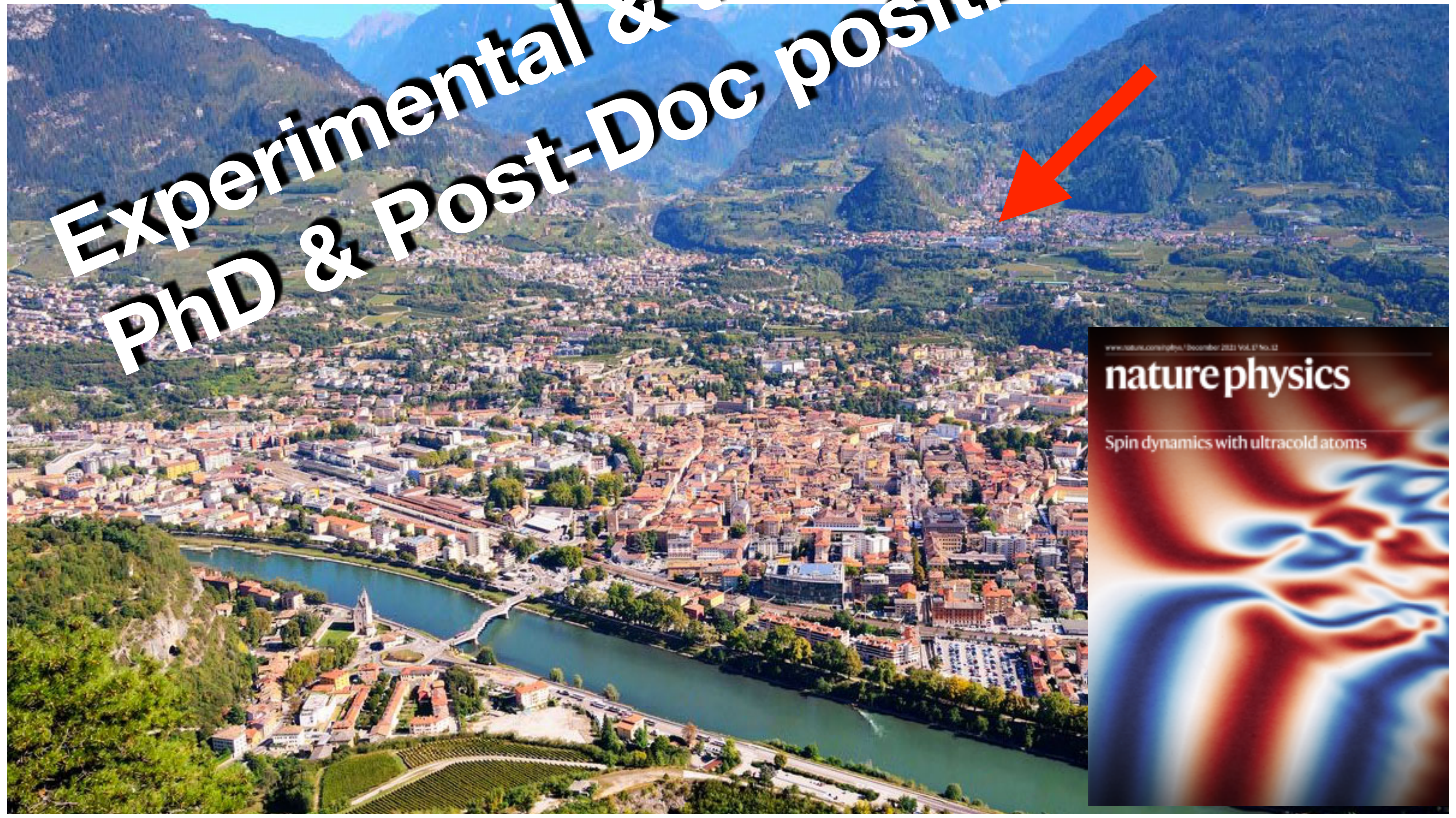


- Also five observed!

Thanks

universität innsbruck

Experimental & theoretical
PhD & Post-Doc positions



Ultracold Sodium
for
Analog Gravity
Vortices
Magnetic interfaces
False vacuum
...

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